Final report of the Study on common specifications for road markings and road signs

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RMSF - ROAD MARKINGS AND ROAD SIGNS FOR THE FUTURE

Final report of the Study on common specifications for road markings and road signs

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EXECUTIVE SUMMARY

The objective of this study is to provide the Commission and Expert Group on Road Infrastructure Safety (EGRIS) with an up-to-date information to support the work on the implementation of Article 6(c) of the Directive, with the overall aim of improving the readability and detectability of road markings and road signs, both for human drivers and ADAS systems. The study has been divided into five work packages (WPs) which are interconnected and provide a comprehensive and leading-edge information to the Commission and EGRIS.

The main aim of the first work package (WP1) was to review current practices, procedures, methodologies, requirements and standards regarding road markings and road signs among MS and thus identify strengths and limitations as well as best practices. A similar analysis was carried out also at the international level, i.e. outside EU (primarily USA and Australia), by researching literature and consulting with stakeholders in the field. In addition, WP1 included a comprehensive literature review of the impact of road markings and road signs on both human and ADAS systems in order to analyse the level of compliance of current legislation, specifications and standards among MS with the minimal needs of human drivers and ADAS systems. Overall, it was concluded that, although road markings and signs in MS are regulated by national regulations, guidelines, specifications and standards, their performance level, i.e. quality characteristics, dimensions and design, differ among MS. Moreover, current standards for visibility of road markings in some countries may not be adequate for both human drivers and ADAS in all conditions. Several opportunities for establishing common specifications were identified based on the analysis.

Those outcomes were discussed at meetings and their overview is incorporated in the second work package (WP2). Tasks within WP 2 included supporting the Commission in preparing EGRIS meetings and meetings of its subgroup 1 "Road Markings and Signs", preparing relevant information and input for the meetings and the work of the expert group, complementing the findings and results of each meeting, and consulting with the relevant bodies of the UN Economic Commission for Europe. At plenary and EGRIS meetings, in addition to the consortium and MS representatives, relevant bodies and external stakeholders also contributed by providing views and suggestions during the development of the study. The result of this work package is a sum of all findings, arguments, discussion and results derived from each meeting.

In parallel with the study of legislation and its applicability to new technologies used by ADAS systems, a thorough investigation and overview of the state of existing technologies was conducted as part of the third work package (WP3). In this part of the study, we analysed market ready ADAS systems, sensor technologies and the level of automation of ADAS systems, especially those expected in the next few years. Based on the work package activities and conducted analysis of the current technology, future trends and road infrastructure, it was concluded that for vehicles up to SAE Level 2, where the human driver is only supported by the system and must be aware of the situation at all times, it is generally sufficient to keep the quality and maintenance of the road markings and signs on a level that is adequate for humans. However, higher automation levels that need high reliability of the system would require changes in the maintenance process, regulation, standardisation and even re-design of road infrastructure to a certain extent.

In terms of ongoing innovations and research activities related to road markings, signs, and ADAS technologies, the fourth work package (WP4) provided insights into developments concerning the materials used for road markings and signs, as well as other innovations that could improve their detectability in the future. Some of the researched technologies such as sensor fusion, digital maps, vehicle-to-infrastructure and infrastructure-to-vehicle communication (V2I/I2V) have been found to have the highest potential for improving the detectability and readability of road markings and signs, thus improving the overall accuracy of ADAS systems.

Findings and results from all the previous work packages laid the basis for a comprehensive overview of requirements for road markings and signs, aimed at establishing an inventory of common recommended specifications. Based on discussions with EGRIS, it was decided to focus only on road markings, due to the lack of more concrete understanding of different aspects related to road signs and their impact primarily on ADAS systems. In order to establish whether a common approach, in the form of common technical specifications or guidelines for road markings in terms of visibility and width, generates road safety benefits, EGRIS group decided to base its further assessment on two approaches (WP5): a break-even cost-benefit analysis; and 2) a social cost-benefit analysis. A break-even cost-benefit analysis estimates additional costs of the intervention and calculates how effective the intervention would need to be in reducing the number of crashes or injuries in order for the saved societal crash cost to outweigh the intervention costs. On the other hand, a social or societal cost-benefit analysis of a new road safety measure is a financial calculation that weighs the investment costs of a new measure against the societal benefits that the new measure is expected to deliver (e.g. savings on road casualties). Such an analysis indicates whether the societal benefits outweigh the investment in the measure. For this purpose, a monetary value has been assigned to the benefits that are expected to result from the measure. Preliminary results of both analyses tentatively indicate that introducing common specifications for road markings can potentially result in road safety benefits. However, due to the overall complexity of the problem and the number of factors that impact road safety as well as deficiencies in the data itself, the value of the effect is highly disputable, and results have to be interpreted with a thorough understanding of the limitations of the conducted analysis.

RÉSUMÉ

L'objectif de cette étude est de fournir à la Commission et au Groupe d'experts sur la sécurité des infrastructures routières (EGRIS) des informations actualisées pour soutenir les activités sur la mise en œuvre de l'article 6, point c), de la directive, dans le but général d'améliorer la lisibilité et la détectabilité des marquages routiers (signalisation horizontale) et des panneaux de signalisation (signalisation verticale), tant pour les conducteurs humains que pour les systèmes ADAS. L'étude a été divisée en cinq lots de travail (WP) qui sont interconnectés et fournissent des informations exhaustives et de pointe à la Commission et à l'EGRIS.

L'objectif principal du premier lot de travail (WP1) était d'examiner les pratiques, procédures, méthodologies, exigences et normes en vigueur en matière des marquages routiers et des panneaux de signalisation dans les États membres et de recenser ainsi les points forts et les limites ainsi que les meilleures pratiques. Une analyse similaire a également été réalisée au niveau international, c'est-à-dire en dehors de l'UE (principalement aux États-Unis et en Australie), en effectuant une analyse bibliographique et en consultant les parties prenantes dans ce domaine. En outre, le WP1 comprenait une analyse bibliographique exhaustive de l'impact des marquages routiers et des panneaux de signalisation à la fois sur les humains et les systèmes ADAS afin d'analyser le niveau de conformité de la législation, des spécifications et des normes en vigueur dans les États membres avec les besoins minimaux des conducteurs humains et des systèmes ADAS. Dans l'ensemble, il a été conclu que, bien que les marquages routiers et les panneaux de signalisation dans les États membres soient régis par des réglementations, des lignes directrices, des spécifications et des normes nationales, leur niveau de performance, c'est- à-dire les caractéristiques de qualité, les dimensions et la conception, diffère d'un État membre à l'autre. De plus, les normes actuelles en matière de visibilité des marquages routiers dans certains pays pourraient se révéler inadéquates pour les conducteurs humains et les systèmes ADAS dans toutes les conditions. L'analyse a permis d'identifier plusieurs possibilités d'établir des spécifications communes.

Ces résultats ont été discutés lors de réunions et leur vue d'ensemble est intégrée dans le deuxième lot de travail (WP2). Les tâches dans le cadre du WP2 consistaient notamment à aider la Commission à préparer les réunions de l'EGRIS et les réunions de son sous- groupe 1 « Marquages routiers et panneaux de signalisation », à préparer les informations et contributions pertinentes pour les réunions et les activités du groupe d'experts, à compléter les conclusions et les résultats de chaque réunion et à consulter les organes compétents de la Commission économique pour l'Europe des Nations Unies. Lors des réunions plénières et des réunions EGRIS, outre les représentants du consortium et des États membres, les organismes compétents et les parties prenantes externes ont également apporté leur contribution en fournissant leurs points de vue et suggestions au cours de l'élaboration de l'étude. Le résultat de ce lot de travail est une somme de toutes les conclusions, arguments, discussions et résultats issus de chaque réunion.

Parallèlement à l'étude de la législation et de son applicabilité aux nouvelles technologies utilisées par les systèmes ADAS, une enquête approfondie et une revue de l'état des technologies existantes ont été menées dans le cadre du troisième lot de travail (WP3). Dans cette partie de l'étude, nous avons analysé les systèmes ADAS prêts à être commercialisés, les technologies de capteurs et le niveau d'automatisation des systèmes ADAS, en particulier ceux qui seront commercialisés dans les prochaines années. Sur la base des activités du lot de travail et de l'analyse de la technologie actuelle, des tendances futures et de l'infrastructure routière, il a été conclu que pour les véhicules jusqu'au

niveau 2 de la norme SAE, où le conducteur humain est simplement assisté par le système et doit être conscient de la situation à tout moment, il suffit généralement de maintenir la qualité et l'entretien des marquages routiers et des panneaux de signalisation à un niveau adapté aux êtres humains. Cependant, des niveaux d'automatisation plus élevés nécessitant une grande fiabilité du système exigeraient des changements dans le processus d'entretien, dans la réglementation, dans la normalisation et même une reconception de l'infrastructure routière dans une certaine mesure.

En ce qui concerne les innovations en cours et les activités de recherche liées aux marquages routiers, aux panneaux de signalisation et aux technologies ADAS, le quatrième lot de travail (WP4) a donné un aperçu de l'évolution des matériaux utilisés pour les marquages routiers et les panneaux de signalisation, ainsi que des autres innovations susceptibles d'améliorer leur détectabilité à l'avenir. Certaines des technologies étudiées, telles que la fusion de capteurs, les cartes numériques, la communication véhicule à infrastructures et infrastructure à véhicule (V2I/I2V), se sont avérées avoir le plus grand potentiel pour améliorer la détectabilité et la lisibilité des marquages routiers et des panneaux de signalisation, améliorant ainsi la précision globale des systèmes ADAS.

Les conclusions et les résultats de tous les lots de travail précédents ont servi de base à un aperçu complet des exigences applicables aux marquages routiers et aux panneaux de signalisation, en vue d’établir un inventaire des spécifications communes recommandées. Sur la base de discussions avec EGRIS, il a été décidé de se concentrer uniquement sur les marquages routiers, en raison du manque de compréhension plus concrète des différents aspects liés aux panneaux de signalisation et de leur impact principalement sur les systèmes ADAS. Afin d'établir si une approche commune, sous la forme de spécifications techniques communes ou de lignes directrices pour les marquages routiers en termes de visibilité et de largeur, génère des bénéfices pour la sécurité routière, EGRIS a décidé de baser son évaluation complémentaire sur deux approches (WP5) : 1) une analyse coût-bénéfice du seuil de rentabilité ; et 2) une analyse coût-bénéfice sociale. Une analyse coût-bénéfice du seuil de rentabilité estime les coûts supplémentaires de l'intervention et calcule l'efficacité requise de l'intervention en termes de réduction du nombre d’accidents ou de blessées pour que le coût sociétal économisé sur les accidents soit supérieur aux coûts de l'intervention. D'autre part, une analyse coût-bénéfice sociale ou sociétale d'une nouvelle mesure de sécurité routière est un calcul financier qui met en balance les coûts d'investissement dans une nouvelle mesure et les bénéfices sociétaux que la nouvelle mesure est censée apporter (par exemple, la réduction du nombre de victimes de la route). Une telle analyse indique si les bénéfices sociétaux l’emportent sur l’investissement dans la mesure. À cette fin, une valeur monétaire a été attribuée aux bénéfices attendus de la mesure. Les résultats préliminaires des deux analyses indiquent provisoirement que l'introduction de spécifications communes pour les marquages routiers peut potentiellement se traduire par des bénéfices en termes de sécurité routière. Toutefois, en raison de la complexité globale du problème et du nombre de facteurs qui ont un impact sur la sécurité routière, ainsi que des lacunes dans les données elles-mêmes, la valeur de l'effet est très contestable et les résultats doivent être interprétés en ayant une compréhension approfondie des limites de l'analyse menée.

Review and preparation of an inventory of current practices and procedures on road markings and road signs

Final report of the WP1

June, 2021

Directorate-General for Mobility and Transport
Study on road signs and road markings

SUMMARY

As part of the traffic control plan, road markings and road signs provide road users with information regarding the current and upcoming road situation. Although both the private sector and the national authorities in each Member State are pushing towards improving the overall quality of road markings and road signs, further efforts are needed. Therefore, in accordance with the revised Directive 2008/96/EC on road infrastructure safety management (hereafter referred to as "the Directive"), the Commission has set up a group of experts (Expert Group on Road Infrastructure Safety – hereafter referred to as "EGRIS") to assist it in relation to the implementation of the required provisions of the Directive. One of the tasks of EGRIS is, with the help of the sub-group Road Markings and Road Signs, to advise and support the Commission on how to improve the readability and detectability of road markings and road signs, both for human drivers and ADAS systems. The overall aim of this study is to provide the Commission with an up-to-date information to support the work of the MS' experts for the implementation of Article 6(c) of the Directive.

In order to define common specifications for road markings and road signs, it is necessary to conduct a review of the current practices, procedures, methodologies, requirements and standards regarding road markings and road signs among MS. This report summarises the findings from the described tasks and provides a comprehensive overview of practices and methodologies currently available and used in relation to road markings and road signs. Furthermore, based on the strengths and limitations, several opportunities for the establishment of commons specifications for road markings and road signs are identified:

1) Increase the use of durable materials with increased visibility in wet conditions
2) Implement common minimal levels for daytime visibility of road markings on motorways and primary roads
3) Implement common minimal levels for night-time visibility of road markings in dry conditions on motorways and primary roads
4) Implement common minimal levels for night-time visibility of road markings in wet and rainy conditions on motorways and primary roads
5) Implement common minimal width of road markings on motorways and primary roads
6) Improve continuity of road markings (for example at exit ramps or intersections)
7) Improve the contrast of markings on concrete road surfaces with contrast markings
8) Improve the removal of old markings (traces of markings on the road surface after renewal)
9) Improve continuity of longitudinal road markings at exit ramp or intersections
10) Improve uniformity (design) of road markings
11) Implement common configuration of dashed longitudinal road markings

12) Implement common minimal dimensions of warning, prohibitory and mandatory road signs on motorways and primary roads

13) Implement minimal class of retroreflective materials for road signs on motorways and primary roads (depending on the sign type)

14) Establish digital maps of road markings and road signs

15) Improve the maintenance of road markings and road signs

CONTENT

1. INTRODUCTION

Road accidents are a global social problem. Depending on the country, it is estimated that their costs amount from 1% up to 3% of the gross domestic product [1]. Compared to the global situation, European roads are the safest in the world and overall road safety has improved greatly in recent decades. In the period from 2001 to 2019, the number of road deaths in the EU decreased by 55%. However, the progress is misaligned with established targets and still annually around 25,000 people lose their lives on EU roads with additional 135,000 seriously injured [2]. The fact that fatality rates have stagnated in recent years and even less progress has been made in preventing serious injuries gives additional cause for concern. This is partially due to the dynamic and complex nature of road traffic and the fact that safety performance depends on several interconnected factors which are related to the roadway environment, vehicle, and humans.

Given their propensity for error, humans have long been considered a major cause of road accidents, although external factors to some extent contribute to human error. Roadway characteristics and the vehicle itself can provoke human error and thus be the primary cause of the accident. Accordingly, contemporary road safety strategies clearly distinguish the factors that truly cause road accidents (be it human, environmental, road-related, etc.) and focus on a multidisciplinary and comprehensive approach to addressing this problem. Therefore, the European Commission put forward a new approach to EU road safety policy, along with a medium-term Strategic Action Plan. The "Europe on the Move" package reaffirms the ambitious long-term vision and goal: to move close to zero deaths by 2050. By endorsing the Valletta Declaration on road safety, EU Member States (MS) together set a target to halve the number of serious road injuries in the EU by 2030 from the 2020 baseline. To achieve the planned target, the Commission decided to base its road safety policy framework on the "Safe System" approach. This approach changes the paradigm that "death and serious injury in road accidents are an inevitable price to be paid for mobility", in a way that accidents with aforementioned consequences are largely preventable. The prevention is based on a layered combination of measures related to safe infrastructure, safe vehicle systems, safe road use and better post-crash care.

In the last decade, a significant effort has been devoted to improving infrastructure and vehicle safety systems with the aid of technological breakthroughs. As mentioned earlier, road infrastructure and road surroundings may provoke human error and thus contribute to road accidents. Recent findings suggest that a combination of road and human related errors contributes to about 35% of road accidents which result in fatalities and/or severe injuries [3, 4, 5]. Road markings and road signs are one of the fundamental elements of road infrastructure. Their main task is to provide timely and necessary information to drivers regarding the upcoming situation. In other words, they warn and inform drivers about the conditions and construction characteristics of the road, guide road users through the traffic network and regulate traffic in a safe way.

Although both the private sector and the national authorities in each Member State are pushing towards improving the overall quality of road markings and road signs, further efforts are needed. In particular, current standards regarding road markings and road signs are based on human needs and to some extent may not be sufficient for automated driver assistance systems (ADAS). Consequently, a broader approach focusing on the needs and requirements of both human drivers and advanced vehicle systems is needed.

In December 2019, the EU adopted the revised proposal for amending Directive 2008/96/EC on road infrastructure safety management[1]. The revision of EU legislation on road infrastructure safety management aims to address the high number of road fatalities and serious injuries on EU roads by improving the safety performance of road infrastructure. The amendments extended the scope of the Directive beyond the trans-European transport network (TEN-T) to motorways and primary roads outside the network and to all roads outside urban areas that are built using EU funds.

The amending Directive also aims to improve transparency and the follow-up of infrastructure safety management procedures, and to introduce a network-wide road assessment to map the risks of accidents. Furthermore, it proposes to set general performance requirements for road markings and road signs needed both for human drivers and for automated driver assistance systems (ADAS).

In accordance with the revised Directive, the **"trans-European road network"** refers to road networks identified in Regulation (EU) No 1315/2013 of the European Parliament and of the Council[2]; **"motorway"** refers to a road, specially designed and built for motor traffic, which does not serve properties bordering on it and which meets the following criteria: (a) it is provided, except at special points or temporarily, with separate carriageways for the two directions of traffic, separated from each other either by a dividing strip not intended for traffic or, exceptionally, by other means; (b) it does not cross at level with any road, railway or tramway track, bicycle path or footpath; (c) it is specifically designated as a motorway; while **"primary road"** means a road outside urban areas that connects major cities or regions, or both, belonging to the highest category of roads below the category 'motorway' in the national road classification that has been in place since 26 November 2019.

Therefore, the Commission has set up a group of experts - Expert Group on Road Infrastructure Safety (EGRIS). One of the tasks of EGRIS is, with the help of the sub-group Road Markings and Road Signs and in accordance with Article 6(c), to "assess the opportunity to establish common specifications including different elements aiming at ensuring the operational use of road markings and road signs in order to foster the effective readability and detectability of road markings and road signs for human drivers and automated driver assistance systems".

Thus, the overall aim of this study is to provide the Commission with up-to-date information to support the work of the MS' experts. The study is divided into five working packages:

1. Review and preparation of an inventory of current practices and procedures on road markings and road signs
2. Supporting the work of the MS' expert group
3. Technology review of driver assistance technologies
4. Innovation, new technologies and future trends related to ADAS technologies, road markings and road signs

[1] Directive 2008/96/EC of the European Parliament and of the Council of 19 November 2008 on road infrastructure safety management (OJ L 319, 29.11.2008, p. 59–67)

[2] Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU (OJ L 348, 20.12.2013, p. 1).

5. Gap analysis and recommendations

In order to define common specifications for road markings and road signs, it is necessary to conduct a review of current practices, procedures, methodologies as well as requirements and standards regarding road markings and road signs among MS. Although the use of road markings and road signs has been to some extent unified with the United Nations Treaty on Road Signs and Signals from 1968, and their minimal technical requirements are defined in EN standards, there are still inconsistencies among MS. These inconsistencies are mainly related to the geometric, performance and operational characteristics of road markings and road signs. They may affect the human driver and even more the functionality of some ADAS systems.

In order to successfully execute the objectives of WP 1, the following tasks were carried out:

1) Identifying major factors that influence the readability and detectability of road markings and road signs
2) Collecting existing legislation, technical specifications and standards related to road markings and road signs in MS
3) Comparing current legislation, specifications and standards, and identifying most common practices and differences between each MS
4) Determining compliance of current legislation, specifications and standards among MS with the minimal needs of human drivers and ADAS systems
5) Analysing and comparing practices, procedures and methodologies used in MS and outside MS
6) Identifying strengths and limitations of determined practices, procedures and methodologies, highlighting "good" practices and defining recommendations

The first task was, based on the review of available scientific and practical literature, to identify major factors that influence the readability and detectability of road markings and road signs both for human drivers and ADAS systems. The second task was to collect existing legislation, technical specifications and standards related to road markings and road signs in MS.

Current legislation, specifications and standards were compared for every relevant factor and most common practices as well as differences between each MS were identified. Furthermore, we analysed the compliance of existing standards and specifications with the minimal needs of human drivers and ADAS systems. To get a “full picture”, commonly used practices, procedures and methodologies used by road authorities at international level, i.e. outside MS, were also analysed.

This report summarises findings from the above described tasks and provides a comprehensive overview of practices and methodologies currently available and used for road markings and road signs along with possible opportunities for improvements.

2. IMPACT OF ROAD MARKINGS AND ROAD SIGNS ON HUMAN DRIVERS

Road markings and road signs are one of the main elements of road infrastructure and an important instrument for road traffic management as they fulfil various functions [6, 7, 8, 9]:

- Assist in traffic regulation and route-finding,
- Provide visual guidance information,
- Alert drivers and other road users to specific hazards,
- Provide drivers with necessary preview time during the day/night and various atmospheric conditions,
- Impose legal obligations (e.g., speed limits, stop and give way signs/lines).

The purpose of all these functions is to facilitate efficient and safe travel for all road users. Therefore, road markings and road signs contribute to road safety. Elvik (2010) investigated the relationship between road markings, road signs and their influence on road safety (see Figure 1). According to Elvik, road markings and road signs should meet four basic requirements to reduce road accidents [10]:

- Conspicuity: road markings and road signs must attract attention to be noticed by drivers.
- Legibility: road markings and road signs must be legible and recognisable in all conditions and at relevant distances.
- Comprehensibility: road markings and road signs need to be easily understood by drivers.
- Credibility: drivers should act according to the message/information provided by road markings and road signs.

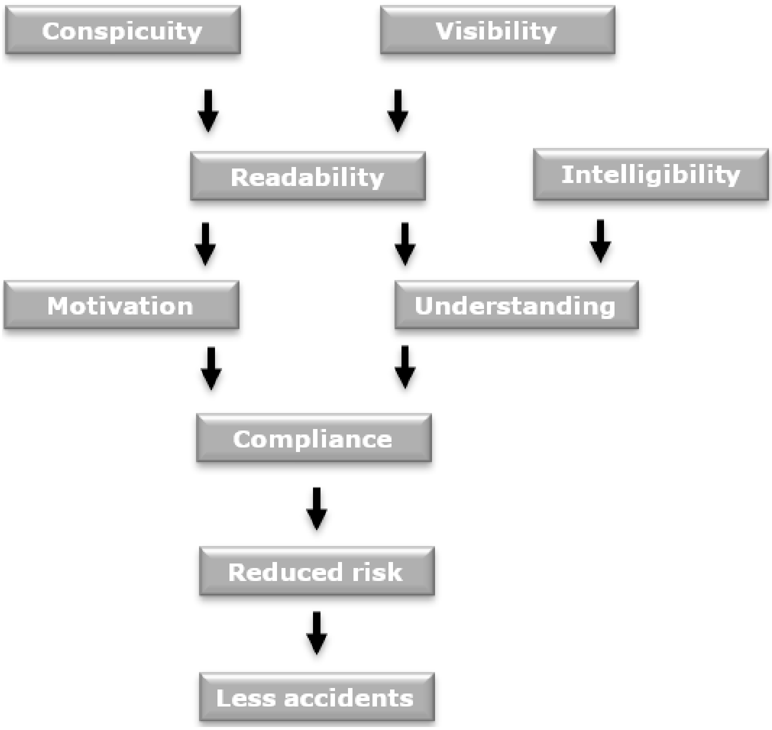


Figure 1. The relationship between road markings, road signs and traffic safety (Source: adapted from [10])

As indicated in Figure 1, these four requirements have a hierarchical order. For a road marking or road sign to be effective and beneficial for road safety, all four conditions must be met in a hierarchical sequence. The first to be met are the conditions regarding the conspicuity and visibility of road markings and road signs in order to ensure good readability and comprehensibility. For instance, road signs and road markings with low conspicuity and visibility, either because they are poorly positioned or have low retroreflectivity/contrast levels, will unavoidably also show poor readability and comprehensibility. This, in turn, will lead to poor credibility or driver compliance. Also, Elvik in [10] highlights that the comprehension and compliance of road markings and road signs are influenced by driver-related aspects such as motivation and understanding, which are affected by how conspicuous, visible and readable road signs and road markings are for human drivers.

The following sections present the main findings regarding the impact of road markings and road signs on human drivers' behaviour and overall road safety. Relevant data was collected from a review of the scientific and professional literature obtained from the relevant databases (Web of Science, Current Content, Scopus, IEEE, TRB etc.) and through consultations with different stakeholders active in this field. In addition, relevant data was also collected by using consortiums' international contacts.

2.1. Road markings

Road markings delineate the road using lines, text and symbols aimed at providing visual guidance information to drivers and other road users [11]. They provide spatial awareness by delineating the road's boundaries, indicating directions and defining the vehicle path through edge and centre lines [8, 12]. In that respect, road markings' most critical function is to prevent vehicles from colliding by encouraging lane keeping [8]. Additionally, road markings provide a good perception/conspicuity of driving lanes and help drivers categorise the road through visual cues that drivers can use to intuitively understand the nature of the road and the expected driving behaviour [13].

To date, several studies have provided convincing evidence of the positive impact of road markings on driver behaviour and road safety. The most important findings of these studies are described in the following sections.

2.1.1. Impact on driver behaviour

A considerable amount of literature has been published on the impact of road markings on driver behaviour and reported their significant impact on the vehicle's lateral position and driving speed.

a) The impact of road markings on lane keeping

Dudek, Huchingson & Woods [14] and Dudek, Huchingson & Creasy [15] investigated the impact of different lengths of broken (edge) lines. They found no significant impact on driver behaviour in terms of driving speed, distance, erratic manoeuvres and the vehicle's lateral position to the centre line.

However, there is evidence that centre and edge lines influence the vehicle's lateral position. Several studies concluded that drivers tend to drive closer to the centre line on roads without edge lines [16, 17, 18]. This behaviour might be explained by the fact that the centre line is located on the driver's side of the vehicle, providing a clear and convenient reference used by drivers for lateral lane positioning in the absence of road edge demarcation [6]. Driving closer to the centre line reduces the probability of running-off road crashes and increases head-on collision risk, especially on two-lane roads. Lundkvist, Ytterbom & Runersjoe (1990) found that wider continuous edge lines (20 cm instead of the conventional 10 cm wide) on a two-lane road positively affected the lateral position of the vehicle [18]. Drivers drove closer to the edge of the road, increasing the distances between passing vehicles and, consequently, reducing the risk of head-on collisions. Furthermore, the authors report that wider edge lines lead to improved visual guidance for drivers at night. The studies by Davidse et al. [17] and Chang et al. [16] confirm the findings of Lundkvist et al. [18] as they also concluded that drivers change the position of the vehicle to be closer to the edge of the road in the presence of centre and edge lines.

The presence of centre and edge line markings is beneficial for the lateral position of the vehicle. As Lundkvist et al. concluded in [18], the width of road markings also positively affects driver behaviour. In Europe, some countries already apply wider road markings: Belgium, Denmark, Germany, and Sweden apply markings with a width of up to 30 cm [19]. Furthermore, Sweden has increased the width of edge line markings from 20 to 30 cm and from the centre lines from 10 to 15 cm to improve visual guidance at night [19]. The European Road Assessment Programme also advises applying a minimum width of 15 cm for road markings [20]. Several studies have shown that wider road markings play a role in reducing crashes at curves and during the night [16, 21, 22, 23]. According to Gates et al. [22], wider edge lines are advantageous in the following situations: locations where a higher degree of lane definition is needed (curves, highways with narrow or no shoulder, work sections), road (sections) with low illumination or low contrast of road markings, and roads where older drivers frequently drive. Benefits of wider roads markings are greater long-range visibility at night, better peripheral vision and improved control and lateral position of the vehicle [22]. Park et al. [23, 24] investigated the effect of wider edge lane markings on crash reduction by comparing rural, two-lane segments in Kansas, Illinois and Michigan for which the edge line width changed from 4 inch (10 cm) to 5 or 6 inch (15 cm). The results indicated that wider markings lead to the following crash reduction estimates: total (5.8 percent), fatal and injury (24.6 percent), PDO (3.9 percent), daytime (10.9 percent), night-time (3.6 percent), daytime fatal and injury (28.7 percent), night-time fatal and injury (39.5 percent), wet (30.9 percent), wet night (33.2 percent), single vehicle (1 percent), single vehicle wet (27.6 percent), single vehicle night (0.9 percent), and opposite direction (39.3 percent) [23, 24]. All of these crash reduction estimates are statistically significant at the 95 percent level except for night-time, single-vehicle, and single-vehicle night crashes. . A more recent study found that wider road markings (≥15 cm) also reduce the driving speed by 2.91 km/h [21]. In curves, the wider road markings reduced the driving speed on average by 3.1%. A possible explanation for this reduction in driving speed is that wider markings create the perception of narrower lanes, making the driver adopt a more careful driving behaviour by driving at lower speeds. The found speed reductions were the highest for heavy vehicles (reductions of 2,46% during the day and 2,15% during the night) compared to light vehicles (reductions of 2,24% during the day and 1,96%) during the night [21].

b) The impact of road markings on speed reduction and speed limit compliance

Road markings are an effective measure for lane keeping, speed reduction and speed limit compliance purposes. Numerous studies have found that different road marking designs such as flat transverse lines, transverse rumble lines, herringbone and dragon teeth patterns, and optical circles are practical measures for speed limit compliance and speed reduction. More specifically, flat and transverse rumble lines effectively reduce speed before curves, intersections, and rural-urban connectors and transitions [6]. Maroney and Dewar in [25] investigated the impact of flat transverse road markings on driving speed by painting transverse lines at progressively diminishing distances on the road surface to produce an illusion of vehicle acceleration. The results indicated that flat transverse lines could reduce excessive speeding behaviour by 40%. Another study by Godley et al. [26] concluded that flat transverse lines are effective at reducing vehicle speeds at an intersection by up to 11 km/h, both immediately after entering the zone with the transverse lines (alerting effect) and throughout the transverse line area (perceptual effect). Near curves, transverse rumble strips lead to mean vehicle speed reductions of -5.3 to -9.8 km/h at 166m before the curve and -3 tot -8.9 km/h at 50m before the curve [27]. Consequently, these mean vehicle speed reductions would result in a decrease of 18.7–39.1% for fatal crashes and 7.8–17.6% for injury crashes compared to the situation with no transverse rumble strips [27]. Besides transverse rumble strips, perceptual treatments such as coloured transverse strips, dragon teeth markings and coloured median islands are also an effective measure to reduce speed in the approach tangent and inside curves [28, 29]. It was found that investigated dragon teeth markings' speed-reducing effect before intersections and found a significant speed reduction equal to 6 km/h at 75 m before the intersection [28]. Also, these perceptual treatments lead to significant speed reductions of 12 km/h compared to a curve with no treatments and 6 km/h compared to a curve with transverse rumble strips [29].

Herringbone patterns are more effective in reducing the driving speed along curves. Their application resulted in lower mean speeds at the curve entry, curve middle and ¾ curve of 2.5–3.5 km/h [27]. Therefore, they have the potential to reduce the number of fatal and injury accidents by 17.9–26.4% and 6.6–9.6%, respectively, depending on the exact position of accidents along the curve (i.e., entry, ¼, middle, ¾ or end). Additionally, herringbone patterns lead to a better lateral position of the vehicle in a curve, which reduces the risk of head-on collisions [6].

Optical circles appear to be an effective perceptual measure to alert drivers to road transitions between rural and urban areas. Hussain et al. [30] found that optical circles with increasing size influenced driver behaviour by reducing vehicle speeds (up to 5.76 km/h) and also keeping them lower over an entire course of 500 m (300 m before and 200 m after the transition).

2.1.2. Impact on road safety

Much of the current literature related to road markings' road safety effects pays particular attention to the visibility in terms of detection, recognition distance and minimal retroreflectivity values for drivers in various conditions. Another topic that is frequently addressed is the impact of road markings on crash occurrence.

a) Visibility and retroreflectivity of road markings

Visibility of road markings is defined as the ease with which drivers can see and follow road markings [31]. From a safety point of view, drivers must observe and understand road markings from a proper distance, especially since different road marking patterns and colours require other driver actions (i.e., exiting, lane changing etc.). In general, road markings are designed for a specific preview time, defined as the amount of time that drivers look ahead while driving [31]. The preview time is influenced by the distance at which drivers can observe road markings, which is primarily determined by the road marking retroreflectivity and width [31]. In other words, wider road markings and road markings with higher retroreflectivity require shorter preview times as drivers can faster observe them. This is also confirmed by Finley et al. [32] and Aktan & Schell [33], who found that higher retroreflectivity levels increase markings conspicuity as the maximum detection distance from which drivers can observe and process the road marking information significantly increases. Evidence recommends a preview time from 3 to5 s: with 3 s as the absolute minimum and 5 s as the recommended preview time [34, 35]. Furthermore, if there is concern about the visibility of road markings it is recommended to apply the road marking width of at least 15 cm [22]. The road marking width of at least 15 cm (i.e. 3 cm wider than the currently used 12 cm in the EU) is especially recommend for older drivers with often impaired vision [12, 31].

In general, the retroreflection of road markings in daytime and dry conditions is significantly higher than in night-time and wet conditions. There are various reasons for the degradation of retroreflectivity at night-time and under wet-weather conditions. Firstly, in night-time conditions, the amount of light available to the drivers reduces, narrowing the human field of vision and impairing the perception of colour, shape, texture, contrast and movement [6]. Secondly, in rainy conditions, the accumulating water forms a continuous layer on top of the road marking optics. Much of the incident light that would ordinarily be retroreflected is lost due to specular reflection off the surface of this water layer [36]. Thirdly, this same water layer changes the optical efficiency of the road marking optics, creating the illusion that road markings disappear at night and in wet conditions as the water layer prevents any of the available light that is captured by road markings to be reflected to the driver [36]. These reasons make driving during the night and under wet-weather conditions quite demanding and challenging as the decreased visibility of road markings makes lane-keeping and route-choice more difficult. To conclude, road marking materials with adequate performance during daytime and dry conditions often have lower retroreflective efficiency during night-time and in wet-weather conditions. Consequently, road markings' retroreflectivity is a determining factor for their visibility at night and in wet and rainy conditions. In this light, several academic studies have focused on determining the minimum retroreflective levels required for safe driving in different situations. They concluded that the minimum level of retroreflection required by drivers ranges between 100 and 150 mcd/lx/m^2 in daytime and dry conditions, whereas a minimum level of 150 mcd/lx/m^2 is recommended during night-time and in wet conditions [8, 31, 33, 37, 38, 39, 40, 41]. The most recent study conducted by the Texas A&M Transportation Institute aimed to determine what human drivers need for minimum road marking visibility in wet night conditions [42]. The project included a comprehensive literature review, human factor study which evaluated the visual quality of 20 different road marking samples in dry and continuous wet night conditions on a closed test track facility and retroreflection measurements of road markings, all in order to help establish initial and maintained wet retroreflective road marking performance levels. Based on the study findings, the researchers recommend installing wet retroreflective road markings with a minimum initial continuous wet retroreflectivity of 200 mcd/lx/m^2 (based on a desired four-year service life) and minimum maintained wet retroreflectivity of 50 mcd/lx/m^2. The aforementioned minimum requirements are also sufficient for older drivers.

However, from a practical point of view, such high minimum values for wet conditions are extremely difficult to achieve as this requires very expensive road marking materials with premium glass beads in combination with frequent maintenance activities. Both aspects are very costly for road authorities and in the end may not guarantee the desired quality in rainy conditions (especially heavy rain). The European RAINVISION project recommends a minimum maintained retroreflective performance level of 35 mcd/lx/m^2 for night-time visibility in wet and rainy conditions and a minimum maintained retroreflective performance level of 50 mcd/lx/m^2 during wet conditions [36]. Both minimum values apply for road markings in use. Nevertheless, recently developed materials and application methods for road markings, such as structured road markings with larger and high refractive index glass beads, enhance the visibility of road markings both in dry and wet-weather conditions [36, 39, 43].

Conspicuous road markings are important to older drivers, given their decreased contrast sensitivity and extended perception-reaction time. Several studies have concluded that older drivers have difficulties observing road markings, which leads to a significant possibility of running over them [44, 45, 46]. Therefore, older drivers need a higher contrast between the road markings and the carriageway to notice the road markings well in advance and to have enough time to act. In general, driver performance in terms of the probability of exceeding lane limits is optimised at a perceived brightness contrast level of 2.0 between the road markings and the carriageway [47, 48]. In other words, road markings should be at least three times as bright as the carriageway to be conspicuous enough for drivers of all age groups.

These findings are confirmed by Staplin, Lococo and Byington [49], who compared the driving performance of 25-year-olds and 75-year-olds. They recommend a minimum in-service contrast level of 3.0 between edge lines and the road surface for intersections without overhead lighting and a minimum in-service contrast level of 2.0 for intersections with overhead lighting.

Road marking retroreflectivity is also influenced by different factors such as quality, embedment and density of glass beads, material type, age, road type, number of lanes per roads, snow maintenance activities, amount and speed of traffic, the direction of stripping, and type and roughness of the road [6]. An experimental study by Gibbons and Hankey [38] investigating the visibility of different road marking materials during night-time and rainy conditions found that wet retroreflective tape provided the longest visibility distance, followed by a profiled thermoplastic. In contrast, large glass beads with standard paint provided the shortest visibility distance. The authors also concluded that lighting improved visibility and mitigated the effects of glare. Another study by Sarasua et al. [50] found that waterborne road markings exhibited 29.8% higher directional readings, whereas thermoplastic road markings exhibited 9.6% higher directional readings. The embedment of glass beads directly affects the retroreflectivity and service life of road markings [6]. Under-embedded glass beads are associated with decreased retroreflectivity and service life. This is also the case for over-embedded glass beads, as the initial retroreflectivity is reduced because the surface through which light can enter the bead and is reflected to the source is smaller [6]. In general, the optimal embedment of glass beads is established to be between 50 and 60% [51, 52, 53]. Zhang et al. [54] studied the impact of bead density on paint road markings' reflectivity. They found that white paint markings have significantly higher (+60%) retroreflectivity values than yellow ones of the same bead density. To illustrate, when the bead density is 15%, white road markings have a retroreflectivity value of 233 mcd/lx/m^2 while yellow road markings have a retroreflectivity value of 144 mcd/lx/m^2. These findings are consistent with a previous study of Craig et al. [55] indicating that white edge lines generally have higher retroreflectivity values than yellow centre lines. Another study by Zhang et al. [56] studied the relation between the type and roughness of the road and road marking retroreflectivity and proposed using thicker and more compact road marking materials on bituminous surface roads.

b) Impact of road markings on crash occurrence

Several studies investigated the connection between road markings and the occurrence of road accidents, especially in night-time conditions. One of the first such studies was conducted in 1981 with the aim of analysing how adding centre and/or edge lines on the roadway affect safety. After comparing the number of road accidents involving injuries and/or fatalities before and after adding centre and/or edge lines, a significant decrease in crashes was reported (ranging from 3%-16% depending on the type of road marking that was added) [57]. A study conducted in 2006 by Tsyganov et al. [58] confirms that edge lines have positive effects on road safety in low visibility conditions. Furthermore, roads without edge lines have an 11% higher road crash risk compared to roads with edge lines. Also, frequently renewing road markings in terms of increasing their retroreflectivity levels results in a 6% reduction in night-time road crashes [59]. On the other hand, Bahar et al. (2006) investigated the relationship between road marking retroreflectivity and safety on multilane freeways, multilane highways and two-lane highways in California and found no measurable safety effect. More specifically, the safety difference between high retroreflectivity and low retroreflectivity yellow and white road markings during non-daylight conditions on non-intersection locations was found to be approximately zero for roads that are maintained at the level implemented by California [60]. However, the study has some limitations. According to the authors, "the study results cannot be used to quantify the safety effect of retroreflectivity greater or less than the ranges modelled for California". Furthermore, it appears that California's level of maintenance seems to be frequent with road markings being installed on higher volume highways up to three times a year with waterborne paint, or every two years with thermoplastic road markings. A similar conclusion was drawn in New Zealand - no significant correlation between the number of road accidents and road markings retroreflectivity was found [61].

Other studies concluded that road markings with higher retroreflectivity are associated with lower crash numbers as they provide better visual guidance [62, 63, 64]. Smadi et al. [64] found a statistically significant but weak relationship between lower retroreflectivity levels and crash probability. More specifically, lowering the retroreflectivity from 200 mcd/lx/m^2 to 50 mcd/lx/m^2 gives rise to a crash probability increase of 35% on freeways and 37% on two-lane roads [58]. The follow-up study by Smadi et al. (2010), further investigated the relationship between crashes and longitudinal road marking retroreflectivity. Retroreflectivity was identified as a significant parameter in crash probability occurrence (at 90% confidence level for white edge lines, at 95% confidence level for yellow edge lines and at 99% confidence level for yellow centre lines) [65]. For white edge lines and yellow centre lines it was found that crash occurrence probability increased when longitudinal road marking retroreflectivity decreased. The authors mention that the extent of the study is not sufficient to identify a definitive relationship but should be interpreted as an indication of a potential relationship between safety and retroreflectivity. Carlson et al. (2013) evaluated relationships between crashes and longitudinal road marking retroreflectivity [66]. The study considered night-time crashes that occurred under dry conditions at non-intersection and non-interchange segments. The effect of retroreflectivity on night-time crashes and single-vehicle night-time crashes with low retroreflectivity (≤150 mcd/lx/m^2) was found to be statistically significant. Furthermore, the results indicate that crash frequency decreases as the centre line retroreflectivity increases and this applies specifically to increases in lower retroreflectivity levels (≤150 mcd/lx/m^2). For white edge lines, the retroreflectivity was also statistically significant for night-time crashes and single-vehicle night-time crashes as the results showed that the crash frequency decreases with the increase of the retroreflectivity of the edge line.

In addition to the impact of road markings on road safety in dry conditions, studies also focused on wet and rainy conditions. A study conducted by the U.S. Federal Highway Administration (FHWA) in 2015 evaluated the before-and-after effects of wet retroreflective road markings in Minnesota, North Carolina and Wisconsin, and found statistically significant crash reductions on freeways and multilane roads [67]. A recent before-and-after study on the same topic concluded that wet retroreflective road markings reduce wet-night crashes by ± 28% due to their improved visibility [68].

To summarize, the results presented in this section indicate that the relationship between road marking retroreflectivity and safety is, due to the complexity of road crashes, quite elusive. Nevertheless, the majority of presented results suggest that a positive relation between retroreflectivity and night-time crashes does exist. Future research should focus on strengthening the understanding of how specific retroreflectivity levels impact night-time crashes.

c) Road marking materials

The effect of different road marking materials on their service life was investigated by Burghardt et al. [69, 70]. They compared cold plastic, solvent-borne paint and high-performance waterborne paint equipped with standard or premium glass beads. Standard glass beads have a refractive index of 1.5 and are typically produced from recycled window glass. In contrast, premium glass beads are constructed from scratch, have an improved refractive index of 1.6-1.7 and are characterised by exceptional surface quality, minimal air inclusion and better scratch resistance [71, 72]. The authors concluded that the use of premium road marking materials results in a prolonged service life; 54% fewer glass beads and 63% less paint would be required over a ten-year life cycle [69, 70]. This increased service life is primarily reached by applying premium glass beads, which due to their characteristics allow for maximum performance of the base layer materials. The combination of solvent-borne paint and premium glass beads also improves service life to a lesser extent [69, 70]. These results show that using premium road marking materials is more durable and sustainable than the standard materials currently applied.

2.2. Road signs

Road signs, also known as vertical signage, communicate vital information, guidelines and warnings on the road as they are designed and placed to assist drivers and other road users [73, 74, 75]. The Vienna Convention on Road Signs and Signals aims to internationally standardise the road signing system in order to increase road safety. It describes how different road signs should be harmonised on European roads. According to this Convention, all road signs are classified into eight categories (A-H) [76]: A - Danger warning signs, B - Priority signs, C - Prohibitory or restrictive signs, D - Mandatory signs, E - Special regulation signs, F - Information, facilities or service signs, G - Direction, position or indication signs and H - Additional panels.

Most human factors on which the literature on road signs has focused include driver comprehension and perception in terms of design and visibility, and the impact of road signs on road safety. The most important findings of these studies are described in the following sections.

2.2.1. *Driver comprehension and perception of road signs*

According to [31], "Road sign comprehension refers to a driver's or road user's ability to interpret the meaning of a sign". Given this, road signs should be designed and located in such a way that road users of all age groups understand their message. The effectiveness of road signs in terms of sign comprehension, perception and processing depends on four processes [77]: sign detection, sign readability, sign comprehension and sign-induced action. Each driver or road user should successfully go through these four stages if a road sign is designed correctly according to the requirements indicated in Figure 2. The requirements listed in Figure 2 are not exhaustive. To illustrate, Gartner et al. [78] also consider the value that a road sign has for a road user, the coding system, the information processing capabilities and the educational background of drivers and road users as requirements for adequate road sign comprehension and processing.

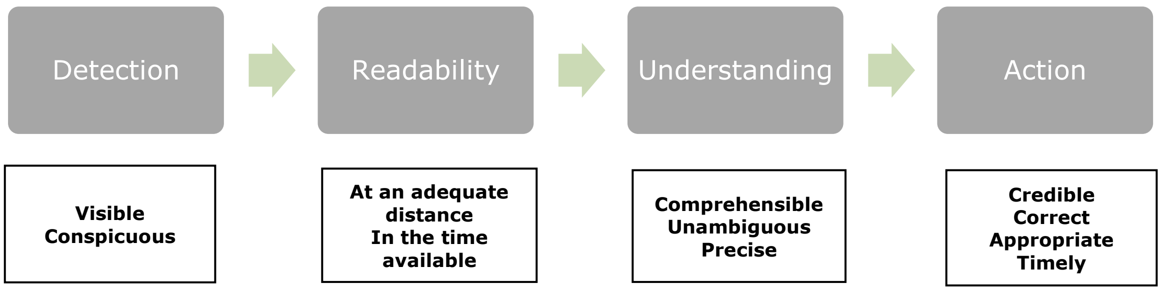


Figure 2. The four stages of road sign comprehension, perception and processing and their requirements [77]

<u>a) Detection of road signs</u>

Conspicuity or visibility of road signs refers to how easy it is for drivers and road users to see and locate a road sign in the surrounding road environment [31]. The more conspicuous the road sign is, the lower is the chance that drivers will miss or are unable to read the displayed information, and the more time drivers have to read, comprehend and act upon the road sign information. During the day, road sign conspicuity means that the road sign face and symbol colours are not faded to such an extent that it is almost impossible to see the message that the sign delivers [31, 73, 79]. Moreover, night-time visibility of road signs implies that the road sign reflects the light from an approaching vehicle's headlights to the driver. Several studies indicated that especially night-time visibility poses a problem for road sign design, as the reduced illuminance conditions during the night/evening are associated with reduced contrast and visibility for drivers of all ages [4, 31, 73, 79, 80, 81]. Additionally, it was found that drivers require a minimum amount of luminance contrast for conspicuity and legibility reasons [80]. Older drivers in particular take more time to scan and process a road sign compared to a typical driver. A meta-analysis of Elvik et al. [4] shows increasing luminance thresholds for sign legibility and conspicuity as the driver age increases.

Furthermore, Mace et al. [82] suggested that the conspicuity of road signs is related to uncertainty, the use of symbols and the purpose of the message. Since these factors are affected by age, they must be considered in determining specific requirements for older drivers. In other words, conspicuity and visibility for older drivers should be a key concern in the design and placement of road signs. Literature underlines that conspicuity may therefore be aided by multiple or advance signing as well as changes in size, luminance and placement of signs [80].

Several studies have investigated the relationship between luminance levels in road sign conspicuity to establish minimum retroreflectivity values for drivers of all ages. In general, literature varies in recommendations for values of road sign retroreflectivity or luminance from 3.2 cd/m^2 to 120 cd/m^2, based on the adaptation level, age, legend, font size, font type, contrast etc. [80, 81, 83, 84, 85]. Eugene et al. [83] recommend a minimum required luminance of around 3.2 cd/m^2 for median driver above the age of 65. However, this value is an absolute minimum and should be avoided on locations where viewing time is limited due to increases in inaccurate sign reading such as during night-time driving [80, 84, 85]. Furthermore, the authors strongly advise that road signs should be replaced before they reach or fall below the minimum luminance level of 3.2 cd/m^2 to guarantee that drivers of all age groups can still detect them. Therefore, 80 cd/m^2 is recommended as an optimum luminance value for road signs to maximise the legibility range in all circumstances and for drivers of all ages [80, 84, 85]. Providing higher retroreflectivity or luminance values is essential as they are associated with longer legibility distances [84, 86]. In other words, more conspicuous or brighter road signs require less information processing time from the driver. Schnell et al. [85] concluded that a 50% reduction in road sign luminance increases drivers' information processing time by 20% to achieve the same response accuracy level. To illustrate, reducing the road sign luminance from the optimum value of 80 cd/m^2 to 40 cd/m^2 results in a 22% increase in drivers' information processing time, leading to a less accurate information transfer.

Retroreflective sheeting materials assist in increasing road sign visibility. In general, retroreflective sheeting materials for road signs are categorised into three classes with increasing luminance values [79, 87]: Class 1 (RA1), Class 2 (RA2) and Class 3 (RA3). When they entered the marked, Class 1 and Class 2 sheeting based their retroreflectivity of glass beads enclosed in the sheeting. On the other hand, Class 3 uses only prismatic retroreflective elements to enable retroreflectivity. Since prismatic retroreflectors have higher retroreflection properties compared to glass beads, in the last decade Class 1 and Class 2 materials are increasingly produced with prismatic elements.

In the past, enclosed glass beads (Class 1 sheeting) were the primary retroreflective sheeting material for road signs. According to today's standards, Class 1 sheeting has a very low retroreflective performance [79, 81, 87, 88]. The retroreflective performance of Class 2 and Class 3 sheeting materials is from seven to ten times greater (dependent on the material) than that of Class 1 materials [89]. Furthermore, Class 3 sheeting is twice as efficient in returning light than Class 2 sheeting [89]. Gatscha et al. [87] tested the retroreflectivity performance of Class 1 and Class 2 sheeting in an on-road test. They found that road signs with Class 1 type sheeting (with glass beads as retroreflective elements) were only bright enough for 42% of the drivers, whereas road signs with Class 2 type sheeting (with prismatic retroreflective elements) were considered bright enough by 74% of the drivers. The authors also advise using Class 2 sheeting as a minimum threshold to meet the retroreflectivity performance requirements of road signs for older drivers.

Another study by Gatscha et al. [88] compared the retroreflective performance of road signs of Class 1, Class 2 and Class 3 sheeting in real night-time driving circumstances. The results indicated that road signs with Class 3 sheeting are superior. Drivers indicated that they could perceive Class 3 road signs faster, even during night-time, followed by Class 2 road signs. Only a small percentage of the participating drivers indicated that Class 1 road signs were bright enough. Given this, the authors concluded that Class 3 road signs positively influence drivers' observation behaviour. The faster perception of

Class 3 road signs gives drivers more time to concentrate on other essential stimuli in the road environment, such as obstacles, other road users, etc., resulting in fewer crashes and road safety benefits. The above findings are confirmed by [79, 81], who also found that Class 3 sheeting has the best performance during night-time conditions as it requires minimum luminance to be visible, followed by Class 2 sheeting. In contrast, Class 1 sheeting has an inadequate performance during night-time conditions. To summarise, Class 3 sheeting has the best performance during night-time conditions but is also the most expensive solution. Therefore, Obeidat et al. [79] recommend that Class 2 sheeting is sufficient to increase road sign visibility and legibility for overhead signs (directional signage) at night for Departments of Transportation with limited budgets, and it would still improve driver safety on roadways.

Concerning the sustainability of road sign sheeting materials, Ye et al. [81] and Preston et al. [90] have shown that Class 2 and Class 3 sheeting have a usual service life of around 15 to 20 years in rural and urban areas. Their service life depends on environmental conditions and in some cases may be up to 30 years [90]. For Class 1 sheeting, the expected road sign service life is lower, namely between 10–12 years. However, longer service life (up to 20 years) is possible [90]. The production of Class 2 and Class 3 sheeting is also more sustainable than Class 1. During the production process of Class 2 and Class 3, the sheeting is associated with 97% decreases in VOC emissions, 46% decreases in solid waste and energy savings of 77% [81, 87, 89].

b) Readability of road signs

The extent to which drivers can read road signs is called sign legibility. Sign legibility is essential for the initial perception of road signs and is determined by parameters such as retroreflectivity (sheeting type), contrast, font size and font style [31]. Increasing sign size and reflectance are the two principal methods to improve sign legibility [80].

Road sign legibility reflects the interaction between the driver, the road sign and the environment. It is essential for all drivers as it largely determines their ability to perceive and understand the message the road sign conveys [31]. In other words, road signs that drivers cannot read from an adequate distance and in the limited time available can be regarded as a road safety hazard. Yee et al. [91] show that due to age-related visual declines 25% of older drivers experience problems reading road signs. Sign placement was the most frequently reported problem, followed by size, contrast and clarity of the message. In general, older drivers require larger road signs with higher contrast values, larger font sizes, simple font styles and symbols, and an optimum luminance value of 80 cd/m² [31, 80, 84, 85].

Drivers read road signs from a moving vehicle. This means that road signs need to meet specific characteristics to enable drivers to read them and quickly process the displayed information. The rule of thumb is that the size of road signs depends on the prevailing vehicle speed and is usually based on the 85th percentile approach speed [7]. The higher the overall vehicle speed, the greater the minimal clear visibility distance for the road sign needs to be. The minimal clear visibility distance should be measured from the middle of the most disadvantaged driving lane to ensure that the driver has an unobstructed view of the road sign.

The size of the road sign is determined by the distance from which drivers should notice the sign in advance and by its font size. This is defined by the legibility index, which indicates the reading distance as a function of letter height and adequate contrast of

5:1 or higher [31, 80, 85]. Schnell et al. [85] studied the effect of letter size on drivers' information processing time and information transfer accuracy from simulated road signs during night-time. One of the key findings of their study is that larger sign size positively influences legibility performance as drivers need less time to read and process the sign information. To illustrate, decreasing the letter size (from 33 foot/inch (3.6 m/cm) to 40 foot/inch (4.8m/cm) legibility index) required an additional 38-percent reading time on average. Other studies also confirm that a maximum legibility index of 40 foot/inch (4.8m/cm) should be used for safety purposes [80, 81, 92].

Furthermore, increasing the contrast from 6:1 to 10:1 does not appear to affect road signs' information transfer performance [85]. Drivers did not process the sign information faster or more accurate when the contrast levels increased. These findings are somewhat contrary to the conclusions from other studies that defined 12:1 as the optimal font and symbol to background contrast value for sign legibility [31, 80, 93]. According to these studies, a contrast value of 12:1 is highly recommended for older drivers in situations with significantly reduced visibility (night-time driving, wet-weather conditions and few auxiliary lighting) and fully reflectorised signs. Schnell et al. [85] also add that higher road sign luminance and larger letter sizes provide more accurate road sign reading when viewing time is limited and that drivers' information processing times are less affected by distance (letter size) if sign luminance is maintained at the optimum level of 80 cd/m².

As mentioned earlier, reflectance improves road sign legibility. Caracoglia [94] assessed the benefits of Class 3 sheeting on drivers' ability to read road signs. Drivers of all ages participated in the study. They evaluated the readability distance of road signs with Class 3 and Class 2 sheeting in terms of sign colours (white/blue, white/green and black/white), entrance angles of 5° and 40°, sign size (small, medium, large) and letter heights (6 cm, 10 cm, 12 cm). The following key findings were recorded for each of the investigated specific road sign characteristics [94]:

- For all colour combinations, road signs with Class 3 sheeting increase the readability distance on average by 36%
- Even for entrance angles of β = 40°, Class 3 sheeting increases the readability distance by 34%
- For all sign sizes, Class 3 sheeting increases the readability distance on average by 35.7%
- For road signs with letter heights of 6 cm, 10 cm and 12 cm, Class 3 sheeting increases the readability distance by 34%, 36.5% and 36.6%, respectively
- When using Class 3 instead of Class 2 sheeting, the readability distance of road signs increases by 29%, 33% and 40% for drivers aged 20, 40 and 60 years, respectively. Furthermore, by using Class 3 sheeting, 60-year-old drivers can read roads signs 6% better than 20-year-old drivers can read Class 2 signs.

In general, the evidence from this study suggests that the readability distance for road signs with Class 3 sheeting is on average 36% higher for drivers of all age groups compared to Class 2 sheeting.

c) Understanding of road signs

Road users' ability to understand road signs is essential to road safety. Road signs that are poorly understood or misunderstood require more information processing time from the driver. Consequently, they can distract the driver, which can cause crashes [95, 96]. Therefore, road signs should be designed and presented in such a way that all road users understand their message. Understandability is considered the most critical design factor for road signs, followed by other criteria such as conspicuity, reaction time and legibility distance [97]. Since well-designed road signs are more efficiently understood, road signs' features (colour, shape, text only, pictorial/symbol only, or mixed) must be selected to maximise information transmission and comprehension [31, 98, 99]. Kraft et al. [100] define a well-designed road sign as "a road sign that complies with a certain need, drawing road users' attention and conveying a message in a clear and simple manner, which gives the user enough time to respond correctly". According to the American National Standards Institute, a well-designed or good road sign is a sign that is understood by at least 85% of the participants in a sign recognition test [101].

The practice is that text-based signs are used to transfer highly complex messages such as route direction/destination. Drivers interpret this type of information more quickly and easily via text [31]. The majority of road signs are, however, pictorial. Several studies have indicated that pictorial signs are superior to text-based road signs because of their increased conspicuity, legibility and comprehension [7, 102, 103, 104, 105, 106, 107, 108]. Edworthy & Adams [106] mention that the main advantages of pictorial road signs lie in the fact that they are recognised more quickly, more accurately, and from a longer distance by drivers from all age groups. Other benefits of pictorial over text-based signs are that they are more easily understood by drivers who do not speak or read the local language and are less vulnerable to degradation effects (rust, fading, mud) [7, 109].

Unfortunately, research has shown that designing well-understood road signs is not that straightforward [7, 75, 102, 103, 104, 105, 109, 110, 111, 112, 113, 114, 115]. It was found that drivers also often misunderstand pictorial road signs. In their study, Dewar et al. [105] found that drivers only understood 40% of the pictorial road signs presented to them. These findings are confirmed by Al-Madani and Al-Janahi [110], who reported understanding levels of 58%. Other studies also demonstrated that most drivers do not misunderstand certain pictorial road signs or interpret them as the opposite of their intended meaning (e.g. 'no entry to motorcycles' was interpreted as 'allowed entrance for motorcycles' by 21% of the drivers) [102, 109, 115]. Shinar et al. [109] studied the understandability of pictorial road signs in four countries and concluded that driver characteristics such as age and gender affect sign comprehension. Male drivers appear to be significantly better in sign comprehension than female drivers. The results indicated that male drivers correctly identified 59.5% of the shown road signs, whereas female drivers correctly identified 57.6% of them. Older drivers also appear to have lower levels of road sign comprehension than younger drivers. This finding is confirmed by Dewar et al. [105] and Ben-Bassat et al. [103], who have shown that sign comprehension is generally 20% lower among older drivers compared to their younger counterparts. Older drivers' inadequate comprehension of road signs is probably the result of their limited exposure to a variety of road signs. Because of age-related constraints, older drivers often limit their driving to their immediate residential environment. Consequently, they are very acquainted with road signs that occur in familiar environments (and can also correctly recognise and comprehend them) but are unfamiliar with road signs placed outside their regular driving environment as they do not tend to travel on non-familiar routes. When older drivers are suddenly confronted with one of these "unfamiliar" road signs, they need much more time to interpret the sign (on average 3.55s while younger drivers only need 1.64s) and often fail to understand the intended meaning [103]. Research also indicated that drivers' perception of road signs declines as they are more familiar with the road environment. Correct road sign interpretation is positively related to familiarity with the road sign and environment [75, 116]. Finally, road signs introduced after the drivers had received their driver's licence are also less known to older age groups than pre-existing road signs because they never learned to interpret them in any formal manner [109, 117].

These findings raise the question whether road sign design needs to pay particular attention to the determining factors that contribute to good understanding of road signs. According to Ben-Bassat et al. [102], well-understood road signs can be achieved using standard shapes, colours and symbols that comply with the compatibility principle of ergonomic symbol design. More specifically, they concluded that road signs were comprehended best if they were consistent with the following basic ergonomic principles:

- physical compatibility: the similarity between the content of the road sign and the reality it represents, such as a road sign with a symbol that depicts a real hazard, e.g., not stopping to give priority to a tram will result in a crash
- conceptual compatibility: the extent to which symbols and codes conform to drivers' associations such as several buildings depicted on a road sign to indicate the start of a built-up area
- standardisation: the extent to which the codes used for different dimensions such as colour and shape are consistent for all road signs. For example, warning, instruction and information signs are recognisable due to the distinctive features in terms of identical colours and shapes that are used per type of road sign
- familiarity: the extent to which the driver is acquainted with the road sign from their driving experience.

Other studies supported the findings of Ben-Bassat et al. [102]. They confirmed that drivers better comprehend road signs which comply with these ergonomic principles as they perceived them to be more familiar, concrete, meaningful and straightforward [7, 75, 104, 107, 112, 118].

According to Ben-Bassat [112], ERF [12] and Jamson & Mrozek [7], the crucial reason for the miscomprehension of road signs is their variety and the use of different signs to communicate the same information in other countries. Jamson & Mrozek [7] also mention that the ergonomic principle of standardisation is the most essential for comprehension. Despite the Vienna Convention, which most European countries have ratified, road sign design standards and regulations still vary significantly among countries [7, 76, 112, 119]. However, the standards laid out in the 1968 Vienna Convention do not cover all country-specific needs and situations, giving rise to a variety of road signs with the same meaning, as illustrated in Figure 3. Standardisation in terms of using similar shapes and colours for road signs of the same category (i.e., the ones that communicate the same type of information) is essential from a road safety perspective. In traffic situations where drivers experience high stress or workload levels, it is crucial that they instantly recall the meaning of the road sign in order to avoid crashes [7]. Furthermore, Theeuwes et al. [120] also concluded that standardisation in design improves drivers' adherence to traffic regulations. In this light, it is highly recommended that road signs meet the four ergonomic principles. Particular attention should be paid to the standardisation of road signs (e.g., size of signs, colour use, font size, etc.) to ensure greater uniformity for road signs across Europe. A higher level of road sign standardisation will be especially beneficial for the European cross-border road traffic, resulting in a more familiar driving environment [73]. Finally, road safety will also improve as potential hazardous traffic situations created by the drivers' misunderstanding of road signs will be reduced.

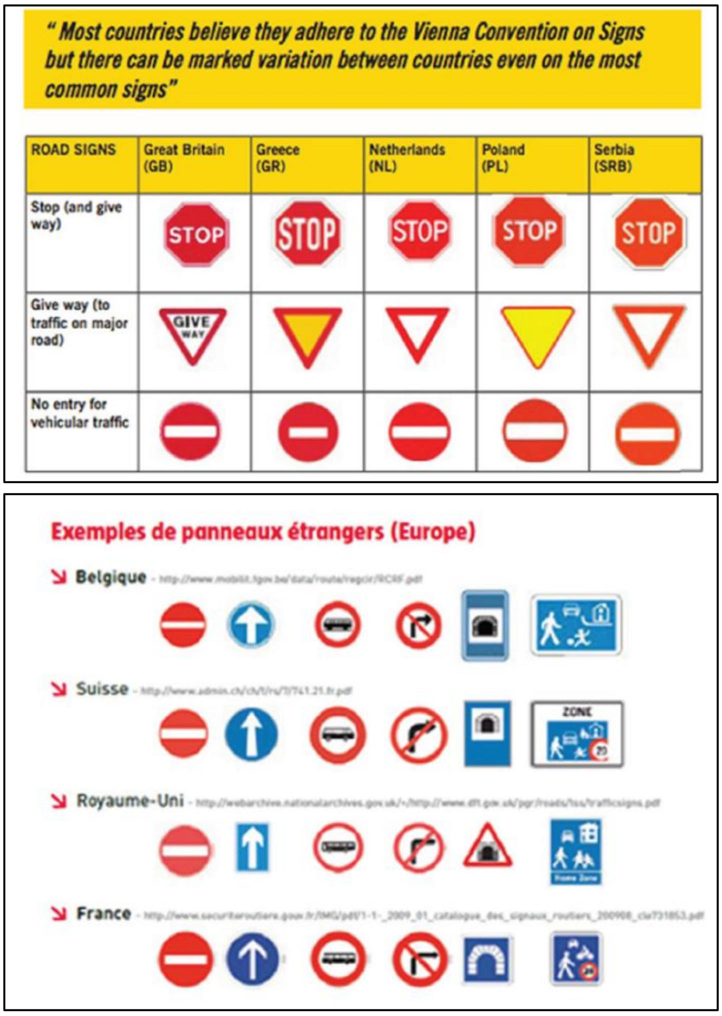


Figure 3. Illustration of different road sign design characteristics in European countries [73]

2.2.2. Impact on road safety

For road safety reasons, road signs are only effective when they are visible. Therefore, they must be and stay in compliance with the minimum retroreflectivity standards. It is unavoidable that the retroreflective properties degrade over the lifespan of road signs due to their exposure to environmental conditions such as sunlight, moisture and pollutants or in case of damage (e.g. vandalism) [9, 74]. In practice, many road signs fail to meet the minimum desired retroreflectivity standards due to cut-backs in public spending, creating an unsafe road environment for all road users [9, 73]. Khallikah et al. [74] investigated road sign failure's impact of faded, cracked and vandalised signs on retroreflective performance. They concluded that faded and cracked signs' retroreflective performance was approximately 15 times lower than for non-damaged signs. Additionally, vandalised road signs had a retroreflective performance that was 1.61 times lower. Several studies also investigated the relationship between invalid road signs and crash occurrence [121, 122, 123]. Road signs can become invalid due to a combination of factors such as sunlight, rain washing, erosion, etc. All these factors or a combination of these factors can cause road signs to become invalid and more difficult to read for the driver. The results of aforementioned studies indicated that if there is an additional invalid road sign per kilometre, the crash rate for material-damage only and fatalities and injuries could increase by 25% and 34% respectively. Penmetsa and Pulugurtha [124] suggest that retroreflective valid road signs help make the road environment safer. With the above in mind, road signs must be maintained regularly and replaced when their visual performance deteriorates under a certain threshold level. To avoid unsafe situations, it is recommended to check road signs' performance every two years [9, 73].

Other studies also investigated the impact of road signs on road safety focusing on the safety effects of supplementary or co-locating signs [125, 126]. Due to limited road space, multiple directional road signs are often placed on the same gantry or below other road signs. These studies found no negative impact on general driving performance in terms of collision rate, reaction time and minimum headway in response to the emergency event. The minimum reaction time of drivers appears to be somewhat slower under sign co-location (no co-location (1.05s), dual co-location (1.91s), and triple co-location (1.66s)), and this did give rise to hazardous situations. Furthermore, even though reaction time is slower under sign co-location, the minimum headway distance to an emergency event did not vary significantly (no co-location (1.62s), dual co-location (2.12s), and triple co-location (1.42s)). The results did, however, indicate that co-locating signs may have some implications regarding travel speed. At some point, almost all participants drove above the speed limit. However, the mean percentage of the time they were driving over the speed limit did not significantly differ among the conditions (no co-location = 8.00 min (SD = 1.96), dual co-location = 4.12 min (SD = 1.63), triple co-location = 9.60 min (SD = 3.79)) [125]. To summarise, supplementary or co-locating of road signs has no significant negative impact on driving performance as drivers can correctly choose their destination regardless of whether the signs were co-located or not [125]. Metz et al. [126] suggest that this is due to the effective attentional strategies which drivers use while searching for directional information.

2.3. Conclusions

Road markings and road signs are common elements of transport infrastructure. They are daily guiding drivers and providing them structure in the complexity of the road environment. The purpose of this review was twofold:

- To determine the impact of road markings and road signs on driver behaviour and road safety
- To identify and define significant factors that influence the readability and detectability of road markings and road signs for human drivers.

The main findings regarding the minimum design requirements for road markings and road signs are summarised in Table 1. The evidence indicates that road markings that meet these requirements have beneficial effects on driver behaviour in lane keeping, speed reduction and speed limit compliance. Furthermore, road marking materials with higher retroreflectivity values create road safety benefits associated with fewer crashes. This analysis has also shown that road signs that meet these requirements are better perceived and comprehended by drivers of all age groups.

In the coming years, Europe will face a significant shift in the age distribution of population. Currently, elderly citizens make up 18% of the European population.

However, by 2030 and 2050, 24% and 28% of the population respectively will be 65 years or older and an increasing number of elderly citizens will actively participate in traffic [127]. In light of the expected increase of the ageing population, future road markings and road signs must correspond to the needs of the elderly. Therefore, it is recommended to adopt a design which will achieve good quality road markings and road signs for every age group. Applying the minimum design requirements listed in Table 1 will contribute to achieving well-designed road markings and road signs in Europe that are visible at all times irrespective of light conditions (day vs night), weather conditions (dry vs wet and rainy) and age (young vs older drivers).

Well-understood road markings and road signs are the first step to achieving a safer road environment. In general, it seems that despite the 1968 Vienna Convention, road sign design standards and regulations still vary significantly among countries. The variety of road signs among countries is especially problematic in terms of cross-border road traffic that continues to grow in Europe. Different designs of road signs conveying the same meaning can cause drivers to misunderstand them, which can lead to hazardous traffic situations. For road safety purposes, it is recommended to ensure a greater standardisation of road signs in Europe (e.g., by using standard shapes, colours and symbols, font size etc.) in order to increase recognition, comprehension and readability. Standardisation in road sign design will also lead to safety benefits as it will ultimately improve drivers' adherence to traffic regulations. In this light, it is highly recommended to policymakers and sign designers that road signs meet the four ergonomic principles of physical compatibility, conceptual compatibility, standardisation and familiarity. They are maximally advantageous for drivers’ road sign comprehension. Additionally, the number of road signs unique to a country should be kept to the bare minimum.

Applying the minimum design requirements listed in Table 1 alone will not suffice to achieve good quality road markings and road signs. To guarantee that road markings and road signs keep adhering to these minimum standards, frequent road marking and road sign maintenance activities are recommended. In other words, road markings and road signs must be maintained regularly and replaced when their performance deteriorates under a certain threshold. As a rule of thumb, it is recommended to check the performance of road markings and road signs every two years.

Taken together, the findings of this review highlight the most important recommendations and design requirements for road markings and road signs that are essential to provide comfortable and safe mobility for all European drivers.

Table 1. Overview of the minimum requirements for road marking and road sign design for human drivers

Design characteristics	Road markings	Road signs
Preview time	Minimum preview time = 3s Recommended preview time = 5s	
Luminance	• Minimum level of retroreflection required by drivers between 100 and 150 mcd/lx/m² in daytime and dry conditions • For road markings in use a minimum maintained retroreflective performance level of 35 mcd/lx/m² for night-time visibility in wet and rainy conditions and a minimum maintained retroreflective performance level of 50 mcd/lx/m² during wetness conditions is required by drivers. • Higher retroreflectivity values are associated with lower crash numbers as they provide better visual guidance White lines have 60% higher retroreflectivity values than yellow lines	• Absolute minimum level of retroreflection of 3.2 cd/m² for drivers of all age groups • Absolute minimum level of retroreflection of 3.2 cd/m² should be avoided for night-time driving due to inaccurate sign reading • Optimum retroreflection level of 80cd/m² is recommended to maximise legibility range of signs in all circumstances and for drivers of all age groups
Width	• Wider markings (≥ 15 cm) lead to significant crash reductions • In case of concerns over road sign visibility it is highly recommended to use wider markings of ≥ 15 cm	Not applicable
Contrast	• Road markings should be at least three times as bright as the road to be conspicuous enough for drivers of all age groups • Without overhead lighting a minimum in-service contrast level of 3.0 between the road markings and the road surface is recommended • With overhead lighting a minimum in-service contrast level of 2.0 between the road markings and the road surface is recommended	• Minimum symbol to background contrast value for sign legibility is 6:1 or higher • Optimal symbol to background contrast value for sign legibility is 12:1 for older drivers in situations with reduced visibility (night-time driving, wet-weather conditions and limited auxiliary lighting)
Font size	Not applicable	• Increased sign luminance and font sizes reduce road sign reading time and improve the accuracy of road sign reading • A maximum legibility index of 4.8m/cm is recommended for road safety purposes

Material type	• Wet retroreflective tape provides the longest visibility distance • Optimal embedment of glass beads is between 50-60% • Premium road marking materials (premium glass beads, solvent-borne paint) lead to a prolonged service life	• Class 2 sheeting is recommended as a minimum threshold to meet the retroreflectivity performance requirements of road signs for older drivers • Class 3 sheeting road signs are superior in terms of brightness, drivers' readability distances and service life
Standardisation	• Well-understood road markings and road signs can be achieved using standard shapes, colours and symbols • Standardisation in design improves drivers' adherence to traffic regulations • Particular attention should be paid to the standardisation of road signs (e.g., size of signs, colour use, font size, etc.) to ensure greater uniformity of road signs across Europe	

3. IMPACT OF ROAD MARKINGS AND ROAD SIGNS ON ADAS

With new technological breakthroughs in the last decade, a significant effort has been devoted to improving vehicle safety systems. These safety systems can be divided into passive and active systems. Passive systems reduce the injuries sustained by passengers when an accident occurs, while active ones try to keep the vehicle under control and avoid accidents [128]. Overall, their main purpose is to perform different tasks and assist the human driver in driving. Due to their high potential in accidents reduction, Advanced Driver Assistance Systems (ADAS) are one of the fastest-growing safety application areas.

The ADAS are designed to assist the driver by increasing safety, comfort and efficiency regarding ecology, mobility and economics. They cover a wide range of driver support features (SAE Level 0 - SAE Level 2) such as adaptive cruise control (ACC), lane support systems (LSS), autonomous emergency braking (AEB), sign recognition systems, highway assist (ACC + LKA), park assist, traffic jam assist and much more.

Undeniably, safety is the primary motivation for vehicle automation but also remains the greatest challenge. Although human error is a major attributing factor in road accidents, the human driver is still an excellent controller with high perception capabilities and fast decision-making. This sets the bar for ADAS quite high. Nevertheless, ADAS shows great potential in accident prevention. Jermakian estimated that with 100% implementation rate, up to 23% of fatal crashes involving passenger vehicles and 6% of those involving trucks are preventable [129, 130]. Kusano and Gablet [131] show the benefits of forward collision warning (FCW) and lane departure warning (LDW). They estimate that from 0 to 67% of crashes and from 2 to 69% of moderate to fatal injuries in rear-end collisions could have been prevented if all vehicles were equipped with FCW systems. The LDW systems could have prevented from 11 to 23% of drift-out-of-lane crashes and from 13 to 22% of serious to fatal injuries to drivers. Penmetsa estimated that in 2020, 2.7% of single-vehicle lane departure crashes could be avoided in the state of Alabama if 8.5% of the fleet has LSS with 20% effectiveness [132]. Based on the Chinese policy and government plan for market penetration of LSS as well as accidents rate, authors in [133] predicted a reduction by 14.8% for fatalities and 10.1% for injuries if all vehicles incorporate LSS. The AAA Foundation [134] examined FCW, LDW, lane keeping assistance (LKA), AEB and blind spot monitoring (BSM) with respect to their crash-prevention potential. They estimated that those systems when combined could prevent approximately 40% of all passenger-vehicle crashes, 37% of injuries that occur in crashes, and 29% of all deaths in crashes.

Furthermore, several studies evaluated the effectiveness of LSS on real-world crashes. One of the first such studies investigated the effect of lane departure warning on large trucks using carrier-collected data. The results show that trucks equipped with LSS had 48% lower crash rate for the single-vehicle run-off-road, head-on and sideswipe crashes compared to trucks without LSS [135]. An analysis of Swedish national statistics showed that LSS yielded a statistically significant reduction of 53%, with a lower limit of 11%, for head-on and single-vehicle crashes on roads with higher speed limits (70–120 km/h) [136]. Two studies in 2018 recorded similar results. Spicer et al. [137] based their research on crashes which included BMW vehicles in the US fleet and found that vehicles equipped with LSS and auto emergency braking were involved in 13 to 63% less accidents (depending on vehicle type and crash type). Cicchino [138] concluded that, without accounting for driver demographics, vehicles with LSS had significantly lower crash rates of all severities (18%), both in those with injuries (24%) and in those with fatalities (86%). However, the author highlights that the LSS effect is lower when driver demographics were added as a control variable – there was an 11% reduction in crashes of all severities and 21% reduction in crashes with injuries.

The intelligent speed assistance (ISA) [139], which is a traffic sign recognition-based system, is capable of informing drivers of the current speed limit and automatically reduce the vehicle's speed by limiting engine power, if needed. The system has the potential to reduce accidents by 30% and deaths by 20%.

The benefits that ADAS show unquestionably indicate to a further increase in ADAS market size. Those trends go hand in hand with the new EU directive which will make some of the ADAS features mandatory as of 2022.

Since this study focuses on road markings and road signs, in the following sections only relevant ADAS (lane support systems and traffic sign recognition systems) will be described and analysed.

3.1. Lane support systems (LSS)

Nowadays, ADAS such as LSS are common. These technologies detect longitudinal road markings based on machine vision (MV). Since the standards and policies on road marking design and maintenance have been developed with the human driver in mind (human vision), many works in the literature explored the detectability of road markings by MV systems and their limitations.

Lane departure warning (LDW) is the most basic of such supporting systems. It alerts the driver through optical, acoustic or haptic feedback when they approach or cross lane markings. More advanced examples of such systems are lane keeping assistance (LKA), lane centring system (LCS) and emergency lane keeping (ELK). Those systems use steering and braking to keep the vehicle within the lane.

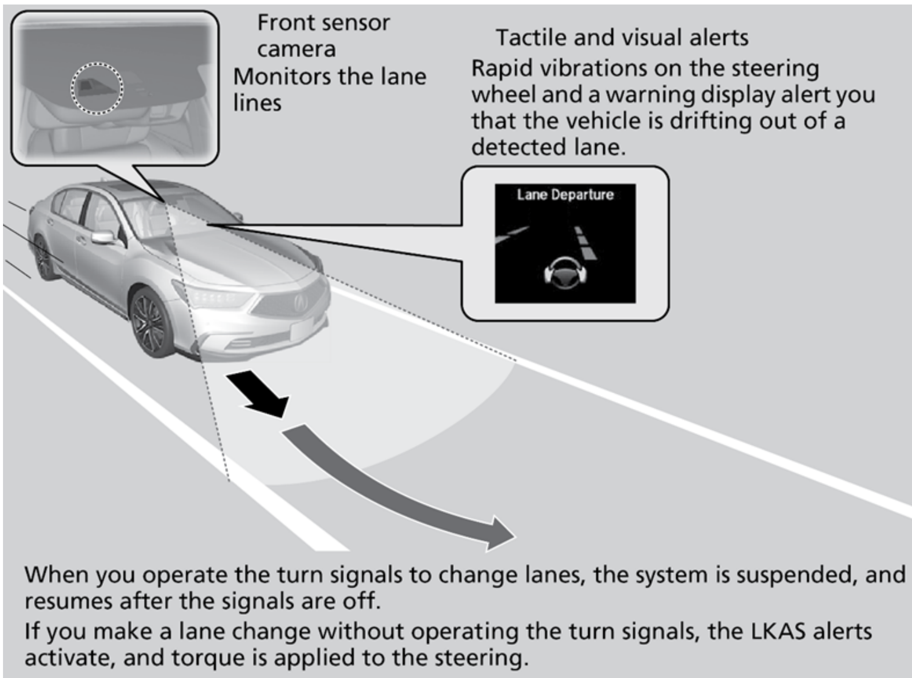


Figure 4. Work principle of LKA (Source: [140])

Despite different feedback, lane detection is a common part of all LSS. Lane detection methods can be divided into traditional and deep-learning methods [141]. The traditional methods [142], in general, include:

1. **Taking raw images** – a camera captures and sends raw RGB colour images to the system.
2. **Image pre-processing** –lens distortion is removed, and different image processing methods are applied like filtering, colour processing and thresholding. This reduces unwanted noise and increases the contrast between road markings and the road surface.
3. **Edge detection and determination of the region of interest (ROI)** – eliminates redundant image data which improves accuracy and reduces the computational load for further analysis.
4. **Lane detection** – lane positions are estimated using feature-based or model-based methods. Estimation is performed by extracting low-level features or using geometrical elements to describe lanes.

After the lane has been detected, the systems constantly monitor vehicle position with respect to the lane positions and send feedback. In advanced lane support systems (LKA & LCS), the system calculates the road course as a base for applying torque to the steering.

Over the past several years, deep learning algorithms became a promising tool in lane detection. They can be grouped into two categories: two-step and one-step [143] algorithms. Two-step methods include deep learning-based feature extraction and clustering/fitting. One-step methods obtain the detection and clustering results directly from the images.

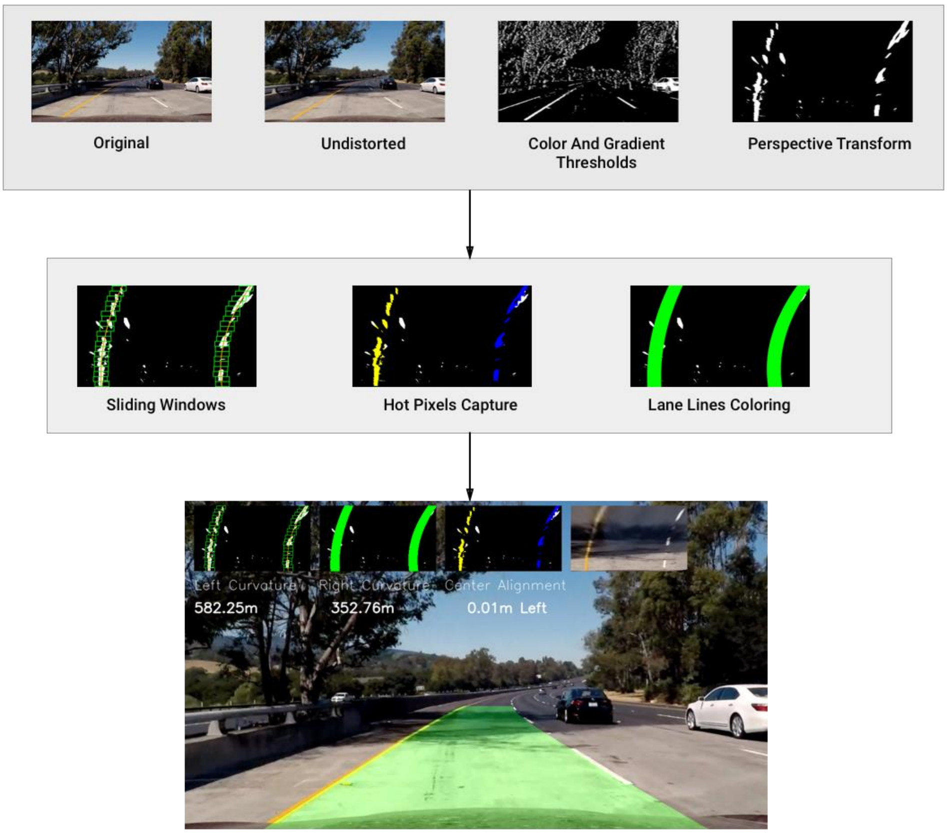


Figure 5. Example diagram of the lane detection pipeline (Source: [143])

As LSS are mainly camera-based, their limitations are associated with low contrast between objects and the background. Another problem that can occur in purely deep learning-based systems is overfitting or limitation due to an insufficient training database.

Low contrast conditions that could lead to insufficient performance of LSS can be caused by:

1. **Environmental conditions:**
   - Adverse weather conditions such as rain or snow
   - Lighting conditions (daytime/night-time or backlight)
2. **Lane maintenance:**
   - Visibility of road markings (e.g. faded)
   - Multiple lane markings such as at construction sites or residuals of old markings
   - Road surface with debris, potholes or cracks that could be misinterpreted by the lane detection system
3. **Others**
   - Lane markings not in normal use
   - Discontinuous markings (e.g. intersection)

Some of the main limitations of LSS are presented in Figure 6.

a) Limitations of lane detection shown on greyscale images

b) Example of seal joint that could confuse MV

c) Example of obscure intersection and exit ramp

Figure 6. Examples of problematic situations for LSS (Source: [144, 145])

3.2. Traffic sign recognition systems (TSRS)

Another important component of ADAS is TSRS, which assists the driver by collecting road-related information. Just like road markings, road signs constitute a fundamental asset of the road. Pedestrians and drivers should easily notice them by day and by night in order to be warned and guided. Consequently, their shapes, colours and positions are designed to be unique and easy to distinguish by humans.

The development of robust real-time TSRS is still a challenging task. In the following paragraphs we are going to present the framework and the limitations that could occur in such systems.

Traffic sign recognition system mostly concerns two related subjects: traffic sign detection (TSD) and traffic sign recognition (TSR). The former focuses on the localisation of the traffic sign in the scenery and the latter performs classification to identify or recognise the detected sign.

a) Traffic sign detection (TSD)

At this stage, MV uses frames of a video to detect any regions of interest (ROIs) that contain the road sign. The literature contains many different techniques. ROIs can be located in the scenery using hand crafted techniques based on the colour, shape or texture or using image processing methods such as Scale-Invariant Feature Transform (SIFT) [146], Histogram of Oriented Gradient (HOG) [147], Speeded-Up Robust Features (SURF) [148].

In recent work, deep learning-based techniques have been used through single shot detector (SSD), faster region convolutional neural network (FRCNN), and you only look once (YOLO) [149]. Another technique used for detection is based on fusion between light detection and ranging (LiDAR) and deep learning techniques (see Figure 7). LiDAR identifies the locations of signs and geometrical structure of the object and then MV generate ROIs and the recognition [150].

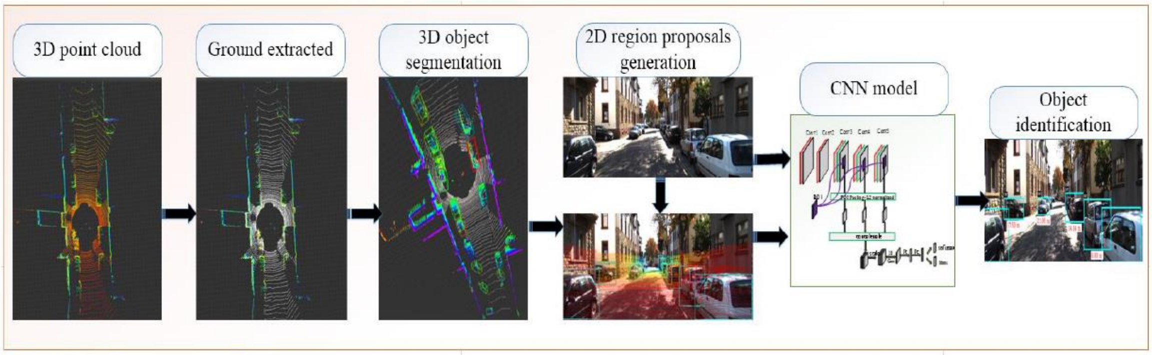


Figure 7. Overview of the framework for the multi-object detection algorithm (Source: [149])

b) Traffic sign recognition (TSR)

In this step, all the detected ROIs are fed into a classifier one-by-one. The road sign is identified based on the characteristics of the input image. Many techniques are used in the classification processes. Machine learning classification algorithms include K-nearest neighbour (KNN), support vector machine (SVM) [151] or DL techniques CNN-based [150].

There are serious concerns about the inadequacies of traffic sign recognition systems and the techniques they use [152].

Potential causes of difficulties are:

1. **Environmental conditions and maintenance**
   - Captured scene quality (motion blur and light condition can alter the clarity of the signs.
   - Road signs condition due to poor maintenance and adverse weather.
2. **System efficiency and accuracy**
   - False positives or false negatives can occur during detection and/or classification.

Some of the main limitations of TSRS are presented in Figure 8.

Figure 8. Examples of problematic road signs for machine vision (Source: [153])

3.3. Literature overview of the impact of road markings and road signs on ADAS

This section presents literature overview of the most important findings regarding the impact of road markings and road signs on ADAS.

3.3.1. Road markings & ADAS

The proper function of LSS and thus their true potential in increasing road safety depends on various factors. For this purpose, several studies were conducted in order to test the functioning of machine vision in various conditions and to determine its minimal performance characteristics.

One of the first such studies was conducted in 2007 with the aim of exploring the efficacy rate of lane departure warning system based on image recognition [154]. The efficacy rate was defined as the ratio of the number of instances in which the lane departure warning device was able to provide lane crossing alarms in all cases when the vehicle crosses lane markings. Besides efficacy rate, authors also observed the number of false alarms, i.e., the number of all instances per mile in which the test vehicle did not cross lane markings and the lane departure warning system was activated. For the study purposes, authors used segments of the Florida Turnpike mainline and its homestead extension. The road was selected because it contains lane markings with varying qualities and types - the marking age ranges from 1 year to more than 4 years, and the retroreflectivity of the markings ranges from less than 100 mcd/lx/m^2 to more than 500 mcd/lx/m^2. Furthermore, authors used LaserLux mobile retroreflectometer to assess the retroreflectivity of lane markings. The test vehicle (the pickup truck with the installed AutoVue system) was driven on the test route during different environmental conditions in both directions of travel. The right (white) and left (yellow) edge lines were intentionally crossed multiple times, and the lane departure warning device performance was observed.

The results indicate that in most cases efficacy rate under dry and light rain conditions is 100%. However, efficacy rate was affected significantly by heavy rain conditions at night for typical lane-marking installations. Moreover, with heavy rain during night conditions, most of the observed efficacy rate values were between 0% and 30%. Although a sample was limited, results suggest that efficacy rate in night rain conditions increased with increased retroreflectivity of the markings. Furthermore, dusk conditions decreased the efficacy rate by 15 to 18%.

Based on the findings, authors concluded that the visibility of the markings under night and rainy conditions should be increased. Several technologies were proposed, such as: the use of large-size retroreflection materials (glass beads) to achieve better visibility and water drainage, the use of profiled markings which have raised profiles with retroreflective materials along the vertical walls to reduce flooding and promote water drainage, and the use of all-weather marking paints and tapes that use special optics to give a high level of dry and wet reflective performance.

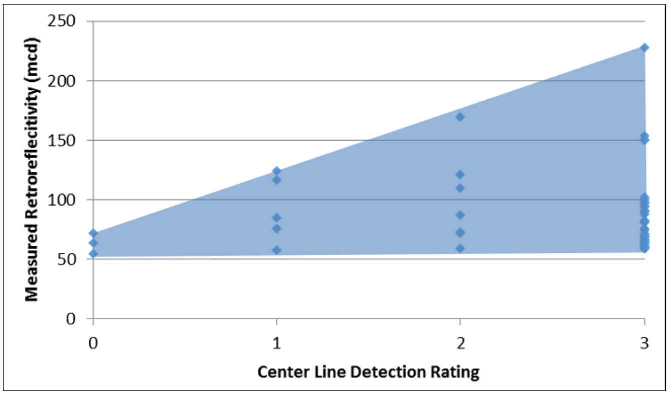
A Swedish study conducted in 2010 tested various types of lane markings (profiled/flat, new/worn) under different light and weather conditions in order to evaluate their detectability by a machine-vision system (camera-based system) [155]. The study concluded that in dry daytime conditions the luminance coefficient must be at least 5 mcd/lx/m^2 higher than the road surface and that it should be at least 85 mcd/lx/m^2. During wet night-time conditions, a minimum retroreflectivity should be 20 mcd/lx/m^2. Furthermore, the results of the study support the use of profiled markings for improved performance under wet conditions. In addition, it is noted that roads wider than seven metres, need to have a centre line for LSS to activate. Finally, the study highlighted the importance of increasing visibility of lane markings under wet and rainy conditions.

In 2011, European Union Road Federation (ERF) released a consultation paper which outlines the minimal standards for road markings in different conditions needed by human as well as automated drivers [156]. The ERF proposed "150*150" system which means that the minimum night-time visibility under dry conditions should be 150 mcd/lx/m^2 and that the minimum width of road markings on all roads should be 150 mm. Furthermore, the minimum night-time visibility under wet conditions should be 35 mcd/lx/m^2.

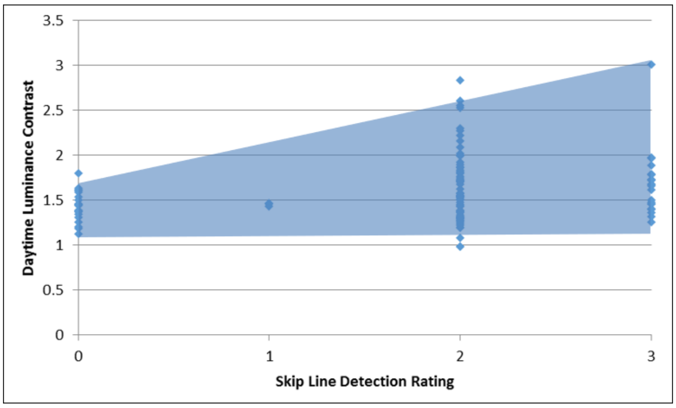
In 2016, a research was conducted with the aim of identifying the effects of lane marking characteristics (width, colour and retroreflectivity) on the performance of machine-vision system [157]. For this purpose, a test vehicle was equipped with a machine-vision system which was modified so that it could be run in a static mode with varying simulated speeds. A set of panels with different road markings was produced (white/yellow, 10/15 cm and varying retroreflectivity levels). The study consisted of three phases. The aim of the first phase was to determine the range of view of the aforementioned system, how road markings detection changes in relation to the driving speed and to environmental visibility conditions (day vs night). Phase two investigated the correlation between road markings' night-time visibility, i.e. retroreflectivity, their detectability by machine-vision and the impact of different contrast ratios between markings and road surfaces. Two different road surfaces with 8 mcd/lx/m^2 and 25 mcd/lx/m^2 were tested in this phase. Phase three analysed the performance of machine vision against road markings of varying width and against various road markings in a wet recovery scenario. For the wet recovery testing, a bucket of water was poured on the markings at the start of the test and all the tests were done at night.

The results of conducted tests indicate that the range of view of the tested machine vision is from 6 to18 meters in front of the vehicle depending on the visibility condition (day vs night). The optimum distance is in the 25-45 feet range (7.6 m – 13.71 m) at a simulated vehicle speed of 56 km/h. With the increase in the simulated vehicle speed (112 km/h), the optimum distance also increased to roughly 25-55 feet (7.6 m – 16.76 m). Furthermore, during the day, the road marking retroreflectivity has little impact on machine vision performance and luminance contrast ratio was the most important factor. On the other hand, at night-time, the road marking retroreflectivity was identified as the most important factor, while retroreflectivity contrast ratio did not show any relevance to the tested machine-vision system. Overall, it was concluded that higher retroreflectivity increased lane confidence, i.e., detectability of markings by machine-vision. Also, wider lane markings (15 cm width) were detected as better compared to narrower markings (10 cm width) regardless of stripe colour.

Similar results were obtained in the 2017 study [158]. The results indicated that the machine vision detection of lane markings generally increased with the increase of retroreflection and contrast ratio as shown in Figure 9. However, authors highlighted that factors such as light bloom from a low-angled sun or a visual occlusion from rain, snow and fog may also influence detection and readability by machine vision. Furthermore, such systems generally detect road markings with the minimal retroreflectivity of 100 mcd/lx/m^2, but do not necessarily provide the strongest detection quality.



a) Retroreflectivity and night-time road marking detection confidence levels



b) Daytime luminance contrast and daytime road marking detection confidence levels

Figure 9. Detection distance compared to different retroreflectivity and daytime luminance contrast levels (Source: [158])

In 2018, Mobileye, as the global camera sensor market leader, produced a summary of road marking challenges with accompanying recommendations. Key recommendations noted in the 2019 report [159] by the American Traffic Safety Services Association (ATSSA) are as follows:

- Line width should be 12–15 cm wide and not more than 25 cm wide
- Lane line length should be standardised, preferably 15 feet long (about 4.5 metres) with a gap of 25 feet (about 7.6 metres)
- Markings should be properly and timely maintained
- Old markings should be properly removed from the road surface
- Higher retroreflectivity levels in wet conditions are needed
- Higher level of uniformity is needed, especially for the arrows and speed bump markings
- The width of "Stop" bars should be uniformed (35–50 cm)
- Consistency of markings is needed
- A clearer distinction between vehicle, cycling and pedestrian areas (shared and/or exclusive) is needed
- Edge of road seals/longitudinal crack sealing can confuse the cameras in certain conditions

In 2020, a study was conducted evaluating eight types of road markings for visibility by machine vision equipment, cameras and LiDARs, under various weather and lighting conditions [160]. The experiment was run at world's largest Climatic Wind Tunnel (Rail Tec Arsenal Fahrzeugversuchsanlage GmbH; Wien, Austria). The study included different road marking materials (white and yellow), from solventborne paint, structured cold plastic and road marking tape with different type of retroreflective materials - premium glass beads with refractive index 1.6-1.7, standard glass beads with refractive index 1.5 and the mix of standard (70%) and premium (30%) glass beads. In addition, the arrangement of markings within the wind tunnel included stripes 6 m long and 0.15 m wide, spaced 0.15 m (except one case) and positioned 10 m away from the sensors. The evaluated machine-vision sensors (positioned 0.65 m above the ground) included three cameras varying in resolution (1.3, 2.3, and 3.1 megapixels) and dynamic range (70 dB and 140 dB) and two LiDARs varying in wavelength (905 nm and 1550 nm). Weather conditions included dry weather, wet weather with various strength of rain combined with wind, and different intensities of fog in which daytime and night-time lighting conditions and glare interference were tested.

The results demonstrate that the response to tested machine-vision systems depended on the equipment itself, daytime (Qd) and night-time (R_L) visibility, quality of retroreflective materials, marking colour and marking structure. The best results were obtained for white agglomerate cold plastic reflectorised with premium glass beads and with white road marking tape (highest R_L). Under wet and foggy conditions, the use of premium glass beads significantly improved the contrast ratio, but no such correlation was recorded for LiDAR intensity. On average, moisture lowered the measured contrast ratio by 80% (range 69%-86%) and LiDAR intensity by 84% (range 72%-96%).

Most recently, the Department of Civil Engineering and Architecture at the University of Catania conducted a study aimed at investigating how different road factors (road characteristics and conditions) impact the performance of the LSS system [161]. For this purpose, researchers used Automatic Road Analyzer (ARAN) to acquire measures of road geometric characteristics (cross section, gradients, horizontal and vertical alignment). The ARAN was additionally combined and synchronised with the Mobileye 6.0 system. The luminance coefficient of the lane marking in diffuse lighting conditions (Qd) was detected with a portable retroreflectometer.

Several on-road tests were performed at different speeds and in free-flow conditions. In total 76 km of road sections were tested during dry and daylight conditions. Along the test sections, lane markings had a constant width of 15 cm with dashed and solid centreline. A Decision Tree Method was used to analyse the collected data and to evaluate the performance of LSS.

Authors concluded that when daytime visibility (Qd) of road markings is lower than 153 mcd/lx/m^2, the probability of LSS failing rises to 11.4% for the calibration sample and 14.35% for the validation sample. Also, curved road sections (with R < 141 m) showed a higher percentage of faults than the average 3% in the test conditions. On the other hand, the average driving speed did not result in any significant changes in LSS accuracy. Overall, the results suggest that a Qd higher than 153 mcd/lx/m^2 improves the detection of lane markings using a Mobileye lane detection system.

Except the aforementioned study, major comprehensive studies were conducted in the US and Australia. The description and findings from these studies are described below in more detail.

a) Texas study

One of the first comprehensive research was a field study conducted at the Texas A&M University System's RELLIS campus with the aim of investigating the effect of the quality of longitudinal white and yellow road markings on the detectability and readability by machine vision system in a vehicle [162]. The researchers used two vehicles equipped with Mobileye 5 which processes images at 15 frames per second, captured by a monochrome camera (1 megapixel) that focuses on road markings located 30-50 feet (approx. 9-15 m) in front of the vehicle. The camera has a horizontal field of view of approximately 40 degrees, and a vertical field of view of approximately 30 degrees. The authors claimed that the tested Mobileye system was by far the most common system on the market when the project started. However, at the time of writing this report newer versions of the Mobileye system have been released that use more recent hardware and software.

The detection confidence rating is an integer value from 0 to 3, with 3 being the highest confidence. Confidence value of 2 or greater is required for the systems to provide lane warning assistance. Confidence ratings of 2 or higher were also defined as adequate. Furthermore, the researcher used handheld retroreflectometers (Delta LTL-XL Mark II and Delta LTL-XL) to measure the coefficient of retroreflected luminance (R_L) and the luminance coefficient under diffuse illumination (Qd), i.e. night-time and daytime visibility of road markings. In addition, a CCD luminance camera was used to measure the luminance (Lv) of the markings under various lighting and wet-weather conditions, and a portable spectrophotometer (HunterLab MiniScan XE Plus) to obtain colour (x, y chromaticity coordinates). However, it must be noted that the geometry of the CCD camera evaluation was not a standard geometry but rather a field geometry representing the geometry at which the MV system was viewing the markings.

The study was divided into two phases. During Phase I (2016), 14 road markings were used, nine of which were white preformed tape markings (including one contrast marking), and five were yellow preformed tape markings. All markings were specially manufactured, i.e., with specific colour and retroreflectivity properties. In this way researchers tried to cover a wide range of road markings quality to simulate varying levels of wear and aging. The majority of the markings had the standard profiled tape pattern, but some were flat. The markings were 4-inch wide (10 cm), installed in pairs in such a way that two markings were observed simultaneously, one on each side of the vehicle. The contrast marking consisted of a 4-inch (10 cm) white marking with 2-inches (5 cm) of black marking on both sides of the white. In addition, markings were evaluated as broken and solid markings. In Phase II (2017) seven test sections containing 11 different markings implemented as solid edge markings were tested. The aforementioned sections consisted of five preformed tapes similar to those evaluated in Phase I, and six water-borne paint markings. Paint markings were applied in thin layer (road surface colour was visible through the material). One pair of paint markings were without glass beads added, the other two with varying rates of Type I beads and black beauty abrasive material to provide some discoloration according to US standard (AASHTO).

Eight scenarios were created to understand the detectability of markings. Each scenario represented different lighting and roadway moisture conditions such as: daytime dry, night-time dry, night-time dry with glare, daytime wet, night-time wet, night-time wet with glare, night-time dry with overhead lighting, and night-time wet with overhead lighting.

The overall results of the study indicate that when comparing the daytime visibility of the markings, the measured values (CIE Y, Qd and Lv) to the road surface had similar contrast ratios across the various road marking performance measures. All markings that had a CIE Y[3] contrast ratio of 2.8 or higher had MV detection confidence ratings of greater than 2 during dry daytime conditions. The markings with a 2.8 contrast ratio had a Y value of 32. All markings with a Y value of 23 or higher had detection confidence ratings of 2 or greater. The markings with a Y value of 23 had a 1.6 contrast ratio.

In wet daytime conditions, the results were influenced by the presence of the sun causing glare on the markings and surrounding road, reducing the detection confidence ratings. Thus, no correlation between detection confidence rating and the marking Y value was found.

For dry night-time conditions it was found that contrast ratios below 2.0 tended to yield the lowest detection confidence ratings. Except in one case, no sample with a contrast value of 2.4 or higher (≥ 30 mcd/lx/m^2) had an average detection confidence rating of 2 or less. The sample with 2.4 contrast values had a retroreflectivity level of 30 mcd/lx/m^2. With the exception of one sample, no sample with a retroreflectivity value of 34 mcd/lx/m^2 or higher had an average detection confidence rating of 2 or less. The limited night-time dry glare testing indicated that markings with a retroreflectivity contrast ratio of 3 or greater had adequate detection confidence by the MV system. All

[3] More commonly used measure in the US compared to the other two.

markings with a retroreflectivity level of 53 mcd/lx/m² or higher exceeded an average detection confidence rating of 2 or higher.

In wet night conditions, every sample with a contrast value of 2.1 or higher had an average detection confidence rating of 2 or higher. In must be noted that during wet conditions the evaluation took place after the markings and road were wetted, but not while being wetted (according to the ASTM E2177).

Continuous markings (solid lines) were more easily detected compared to the discontinuous markings (broken lines). The greatest discrepancies between the aforementioned two types of markings were recorded during daytime. Furthermore, during daytime, road markings detection generally decreased with increased travel speeds. On the other hand, during night-time speed mainly did not affect the detection ratings (in some cases, even a slight improvement in the detection confidence rating as speed increased were recorded). Regarding testing under different levels of cloud coverage, no clear trend was identified. However, only a limited number of observations under cloudy/partially cloudy conditions were observed, based on which more solid conclusions cannot be made. The tests show that surrounding lighting had an adverse effect on detection confidence ratings – with the presence of glare detection ratings decreased. The study also tested one contrast marking and found mixed results. Authors indicate that in specific situations, for example when the sun is causing oncoming glare, the black portion of the contrast may create glare problems instead of mitigating them.

Overall, authors highlighted the need of proper maintenance of road markings in order to generate adequate detection confidence ratings by the machine-vision systems in the vehicle. Authors also concluded that machine-vision systems see similarly to a human, meaning that good road marking practices for a human driver will provide good conditions for the machine-vision system. With the presence of mixed signals, detection of markings will decrease both for the human driver and the machine-vision system. Thus, road marking practices should provide good quality markings in a good state of repair without other signals that could be mistaken for longitudinal delineation.

Based on the test field evaluation, the literature review, and experience in the field, authors identified most important characteristics of road markings for current MV systems:

1. **Road marking presence**
   - There must be a sufficient amount of markings present to be detected.
   - If there is sufficient presence, other characteristics will determine how easily the marking is detected.
2. **Contrast ratio between the marking and road surface**
   - Daytime (CIE Y luminance) - Higher CIE Y value will yield a more visible marking.
   - Night-time (coefficient of retroreflected luminance - R_L) - Brighter markings will have greater benefit the further the MV system looks ahead.
   - Both day and night characteristics depend on the viewing geometry of the MV system.
   - Contrast ratio can be improved by installing a marking with higher CIE Y or R_L characteristics, or by incorporating black marking material in conjunction with the marking.

3. **Road marking width**
   - Wider markings will have greater benefits the further the MV system looks ahead.
   - Larger width of the marking may extend its useful life if the edges deteriorate or presence starts to reduce.
   - Wider markings may reduce negative impacts of conflicting signals, due to their increased signal.
4. **Wet-weather characteristics**
   - Marking texture/structure may be beneficial.
   - Glare situations may be worse in wet situations.
5. **Lane line pattern**
   - Testing indicated that solid markings were better detected compared to broken markings.
   - Optimal configuration has no jet been identified.
6. **Marking texture/structure**
   - May provide benefits in wet conditions.
   - May provide higher rates of detection when glare is present.

Although the study provided some valuable findings, the results are directly applicable only for the evaluated testing conditions and may not be directly transferable to policy or specifications. The testing area had a relatively uniform roadway surface; roadways with conflicting messages from previously removed markings, blackout markings, crack seal, varying road surfaces, cracking, or rutting may require higher-quality road markings. Other limitations of the study which impacted the results and thus need to be taken into consideration are as follows:

- The scope of the study did not allow for several factors to be evaluated at all (impact of raised road markers, wider markings, markings in continuous wetting conditions, shadows or other conflicting signals etc.)
- Some factors, such as glare, contrast markings, configuration of broken lines etc., were investigated just on a basic level
- Only one machine-vision system was used
- The closed course study approach limited the ability to evaluate naturally aged markings
- The tests were done only on concrete road surface
- The visual appearance of the road surface was consistent, allowing the system to possibly detect the markings easier than if the road surface was more variable in appearance or if conflicting signals were present near the markings
- The testing was only conducted in straight tangent sections
- Only a single overhead lighting style/pattern was evaluated.

b) Australian study

Austroads recently published a research report in which they evaluated how longitudinal road markings and different environment weather conditions affect the performance of lane support systems [145]. Based on the defined purpose, two main objectives of the study were to: 1) investigate how to best configure and maintain longitudinal road markings and lane designs to ensure their best possible whole-life performance; 2) determine the level of maintenance required to support machine-vision-enabled, lane-guidance functions.

The project was divided into four parts. In the first part, an extensive literature overview was conducted aimed at understanding the known vehicle-performance characteristics, current infrastructure design and maintenance practices, and vehicle limitations. The literature review served as a basis for other parts of the project. The second part consisted of interviews and discussions with relevant stakeholders. The main aim of this part was to identify current standards and maintenance practices related to road markings and to understand current and proposed machine-vision technologies and how they interact with infrastructure, particularly road markings.

The third part included on-road and off-road test trials. Based on the findings from literature review and consultation with stakeholders, several test cases were developed, and key parameters were identified. These parameters included visibility of road markings (daytime and night-time), line width and width of road lane, conditions of wetness, existence of poorly removed road markings, road condition (crack seal, road joints, shadows, etc.), kerbs and channels, configuration of longitudinal road markings, intersection configuration and driving speed. Seven vehicles with various levels of automated-steering systems participated in the trials. The vehicles ranged from those with minimal LKA functionality, to those with advanced active steering and lane centring. One vehicle was equipped with Mobileye camera and served as a reference vehicle. The visibility of road markings was measured using Delta LTL-M dynamic retroreflectometer and Zehntner ZRM 6014 hand-held retroreflectometer.

The last part of the project consisted in assessing costs and benefits of proposed measures.

Based on the aforementioned methodology, key findings from the project are as follows:

- Daytime contrast ratio between longitudinal road markings and the surrounding substrate should be minimum 3-to-1.
- Contrast ratio for night-time visibility between longitudinal road markings and the surrounding substrate should be between 10-to-1 for asphalt roads and 5-to-1 for concrete roads.
- Overall, the minimal level of road markings night-time visibility should be 100 $mcd/lx/m^2$.
- In general, line detection performance deteriorates as night-time visibility reduces.
- Road "brightness" can degrade machine-vision systems' ability to detect longitudinal road markings in some conditions because it reduces contrast between the road marking and the substrate.

- Daytime visual clutter generally makes daytime lane detection less effective than at night.
- Rain reduced detectability of road markings by 32% of the built-in LKA and 0.92 for Mobileye camera.
- Wet weather has different impacts on different machine-vision-enabled, lane-guidance functions. With minimal ambient lighting the contrast ratio can improve due to reduced specular diffusion, however with excessive ambient lighting the machine-vision systems can suffer from a "light bloom" effect reducing line detection.
- Appropriate width of road markings should be 150 mm for edge lines and 100 mm for dashed lines.
- Dashed lines are more likely than solid lines to be problematic for machine-vision lane detection.
- Using clear continuity lines on both sides of the lane, with no extended gaps and a consistent lane width, is conducive to good lane detection.
- While many difficult-to-control factors can degrade the machine-vision-system's ability to detect longitudinal road markings, improving maintenance standards and design principles can generate significant network-wide gains.
- A cost-benefit analysis found that when longitudinal road markings are improved, the potential discounted crash benefits exceed the discounted capital and maintenance costs by 3.28 benefits-to-costs ratio.

3.3.2. Road signs & ADAS

In recent years, Traffic Sign Recognition System (TSRS) has gained an increasing interest. A vast body of literature analysed the efficiency of different algorithms for segmentation and classification of road signs [163, 164, 165, 166]. Several review papers on this subject have also been published in the last couple of years [167, 168, 169, 170].

Although a number of studies focused on the development of new methods and algorithms for TSRS, only one study conducted a comprehensive analysis of problems and limitations of currently available TSRS. The aim of Austroads study was to identify the root causes of issues related to the proper and accurate functioning of TSRS technology [171]. The objectives of the study were to identify the issues related with current road sign deployments, to define recommendations for changes to road sign guidelines and standards and to develop a program of information and engagement with road authorities. The project was divided into three parts: 1) a literature review of TSRS technology and international road sign standards, 2) stakeholder interviews with vehicle manufacturers and key stakeholders for road sign standards and guidelines, and 3) on-road and off-road tests and evaluations.

The main part of the study is related to the third part, i.e., on-road and off-road tests and evaluations. On-road tests were conducted on motorways and local road routes in Melbourne, Sydney and Auckland, while the off-road trials were conducted at the Australian Automotive Research Centre. In each test, a quantitative and qualitative measures were recorded using in-vehicle cameras and in-vehicle observers. For both tests, researchers included several vehicle models equipped with camera-based TSRS. On-road trials were undertaken in three jurisdictions (Melbourne, Sydney and Auckland) based on the unique nature of their road signage and guidance which allowed for a range of test use cases in live traffic environments. Tests were performed in various conditions - sunny, overcast, rainy, daylight and early twilight. Off-road trials included a range of scenarios which could not be easily replicated in the real world (on-road tests). In such a way a better control of all variables related to road signage (placement, orientation, condition etc.) and environmental conditions was achieved, the spatial databases of speed zones which was, besides camera-based TSRS, used by some vehicles was eliminated, and it enabled the testing of systems in development (pre-market).

The conducted investigation identified the following key issues:

1. Electric signs

Issues

- variable speed limits are not consistently read
- collocation with static speed signs
- inconsistency when reading 30 km/h, 60 km/h and 80 km/h

Root causes

- flickering in the VSLS display
- multiple collocated signage – problem of distinguishing which sign may apply at a given time or under a given condition
- similarity in shape between the numerals

2. Installation and maintenance

Issues

- signs not placed according to standards
- fading, damage, graffiti etc.
- signs not installed by traffic authorities: signs printed on rubbish bins, heavy vehicles

Root causes

- roadworks signs
- TSR systems recognise any valid number within the annulus as a speed limit sign

3. Positioning and collocation

Issues

- Collocated road signs that apply to different motorists
- Roadwork and temporary signage

Root causes

- TSR systems cannot currently interpret text qualifications
- roadworks signs

4. Design

Issues

- Time-dependent speed zones

- Weather-based speed signs

Root causes

- TSR systems cannot currently interpret text qualifications

3.4. Conclusions

The ADAS are designed to assist the driver by increasing safety, comfort and efficiency regarding ecology, mobility and economics. They cover a wide range of driver support features and are one of the fastest-growing safety application areas. Lane support systems (LSS) and Traffic sign recognition systems (TSRS), as important ADAS functionalities, have significant effect on reduction of road accidents. Several studies have highlighted that such systems, depending on several factors (driver demographics, penetration rate etc.) may reduce accidents from 10 up to more than 50%. However, their proper functioning and thus their true potential in increasing road safety depends on a variety of factors.

Key factors which impact the detectability and readability of road markings by machine-vision are related to the:

- Visibility of road markings – night-time (R_L), daytime (Qd) and contrast to road
- Colour of road markings
- Width of road markings
- Road marking configuration (dashed line spacing, exit ramp etc.)
- Environmental lighting conditions
- Weather conditions (rain, fog, snow etc.)
- Road type and texture
- Lane width
- Curve radius
- Driving speed
- Temporary lane markings at construction zones
- Structured/unstructured road edge
- Phantom markings, cracks, repairs, wheel ruts

Main literature findings regarding road markings quality and its impact on machine vision are presented in Table 2.

Table 2. Key findings from the literature

Parameter	Main findings	Type of testing	Source
Daytime visibility (Qd) and contrast ratio	Dry daytime visibility (Qd) must be at least 5 mcd/lx/m^2 higher than the road surface. Dry daytime visibility (Qd) needs to be at least 85 mcd/lx/m^2.	On-road test	Lundkvist & Fors, 2010 [155]
	Road marking luminance contrast ratio (not retroreflectivity contrast ratio) is the most important factor for machine vision performance during daytime.	Off-road test (test field)	Potters Industry and Mobileye, 2016 [157
	Level 2 detection was achieved in most cases for the daytime luminance contrast (not related to Qd) between 1.5 and 2.5.	On-road test	Carlson & Poorsartep, 2017 [158]
	All markings that had a CIE Y contrast ratio of 2.8 or higher had MV detection confidence ratings greater than 2 during dry daytime conditions. All markings with a Y value of 23 or higher had detection confidence ratings of 2 or greater. The markings with a Y value of 23 had a 1.6 contrast ratio.	Off-road test (test field)	Texas study, 2018 [162]
	Daytime contrast ratio between longitudinal road markings and the surrounding substrate should be minimum 3-to-1.	On-road test	Austroads, 2020 [145]
	Qd higher than 153 mcd/lx/m^2 improves the detection of lane markings using Mobileye lane detection system.	On-road test	Pappalardo et al., 2021 [161]
Night-time visibility (R_L)	Dry night-time: a minimum retroreflectivity of 70 mcd/lx/m^2. Wet night-time conditions require a minimum retroreflectivity of 20 mcd/lx/m^2.	On-road test	Lundkvist & Fors, 2010 [154 151]
	Minimum retroreflectivity performance level should be at least 150 mcd/lx/m^2 under dry conditions and 35 mcd/lx/m^2 under wet conditions.	-	EuroRAP, 2011 [156]
	There is a general trend that the machine vision detection rate increases with increased road marking contrast, though not always. Markings with retroreflectivity of at least 100 mcd/lx/m^2 generally can provide suitable detection (not necessarily the strongest one).	On-road test	Carlson & Poorsartep, 2017 [158]
	At night, road marking retroreflectivity is the most important factor. Higher retroreflectivity increased lane confidence.	Off-road test (test field)	Potters Industry & Mobileye, 2016 [157]

	Except one sample, markings with a retroreflectivity value of 34 mcd/lx/m² or higher had an average detection confidence rating of 2 or less. The limited night-time dry glare testing indicated that markings with a retroreflectivity contrast ratio of 3 or greater had adequate detection confidence. All markings with a retroreflectivity level of 53 mcd/lx/m² or higher exceeded an average detection confidence rating of 2 or higher.	Off-road test (test field)	Texas study, 2018 [162]
	Overall, minimal level of road markings' night-time visibility should be 100 mcd/lx/m². Rain reduced detectability of road markings by 32% of the built-in LKA and 0.92 for Mobileye camera.	On-road test	Austroads, 2020 [145]
	Markings with the highest R_L had overall the best results (white agglomerate cold plastic and white road marking tape). Under the conditions of wetness and fog, the use of premium glass beads significantly improved the contrast ratio, but no such correlation was recorded for LiDAR intensity. On average, moisture lowered the measured contrast ratio by 80% (range 69%-86%) and LiDAR intensity by 84% (range 72%-96%).	Off-road test (wind tunnel)	SWARCO study, 2020 [160]
Longitudinal road marking width	The minimal width of road markings should be 15 cm.	-	EuroRAP, 2011 [156]
	Wider lane markings (15 cm width) were detected better compared to narrower markings (10 cm width) regardless of the marking colour.	Off-road test (test field)	Potters Industry & Mobileye, 2016 [157]
	6-inch (15 cm) road markings provide higher levels of machine vision detection confidence in some (but not all) test scenarios, compared to 4-inch (10 cm) markings.	Off-road test (test field)	Texas study, 2018 [162]
	Line width should be 12–15 cm wide and not more than 25 cm wide.	-	ATSSA, 2019 [158
	The appropriate width of markings should be 150 mm for edge lines and 100 mm for dashed lines.	On-road test	Austroads, 2020 [145]
Road marking configuration	Solid lines are more easily detected than dashed lines. The largest discrepancies were recorded during the daytime.	Off-road test (test field)	Texas study, 2018 [162]
	The length of lane line should be standardised, preferably 15 feet long (about 4.5 metres) with a gap of 25 feet (about 7.6 metres).	-	ATSSA, 2019 [159]
	Dashed lines are more likely than solid lines to be problematic for machine-vision lane detection.	On-road test	Austroads, 2020 [145]

With respect to road signs, it can be concluded that there is a lack of comprehensive studies. However, literature identifies several key factors which impact the detectability and readability of road signs:

- Variable lighting conditions
- Fading and blurring effect
- Damaged and partially obscured signs
- Design of the signs
- Visibility of the signs
- Placement of the signs
- Presence of advisory and information signs
- Multiple appearances of the signs
- Refresh rate of signs and variability of pixel illumination of electronic signs
- Unavailability of public database
- Real-time application

4. COMPARISON OF CURRENT SPECIFICATIONS AND STANDARDS IN MS

As stated in the introduction, in order to identify current practices, standards and procedures related to road markings and road signs among MS, a comprehensive questionnaire was defined and sent to the EGRIS experts in each MS. The questionnaire aimed to collect data related to:

1) Current standards and practices related to road markings and road signs
2) The effect of the weather and atmospheric phenomena, and traffic on road markings and road signs on the EU territory
3) The type and frequency of maintenance efforts necessary for various technologies.

The questionnaire comprised 74 questions and was divided into four parts. Part 1 focused on the general information regarding current practices and standards for road markings and road signs in each MS. It contained three subsections: a) General, b) Road markings, and c) Road signs. The first subsection had four questions related to the total length of the roads in the scope of the Directive, width of road lanes, total length of longitudinal road markings and number of road signs on motorways and primary roads. "Road markings" subsection had a total of 18 questions related to the used colours for road markings, width of longitudinal and transverse road markings, types of discontinuous (dashed) lines, used materials for road marking application, quality requirements, and quality control practices among other. In the third subsection, similar questions were asked but related to road signs. The third subsection consisted of a total of 10 questions.

Part 2 focused on the impact of weather and atmospheric phenomena and traffic on road markings and road signs. A total of 18 questions were asked with the intention to determine the climate and traffic conditions in each MS and to what extent such conditions influence the quality and service life of road markings and road signs. Also, several questions were aimed at identifying the use of materials specially designed for improving the quality and durability of road markings and road signs in such conditions.

In Part 3 a total of 12 questions were asked in order to collect information on the maintenance practices of road markings and road signs. EGRIS experts were asked about the frequency of renewal of longitudinal and transverse road markings, frequency of replacement of road signs and the percentage share of renewed and replaced road markings and road signs. The aim of several questions was to identify factors which are considered when deciding about the maintenance of road markings and road signs and the criteria based on which road markings are refurbished and road signs replaced. In addition, information was collected about annual costs of the maintenance of road markings and road signs on roads in the scope of the Directive.

Finally, Part 4 had 12 questions through which EGRIS experts gave their opinion on the general impact of road markings and road signs on the relevant automated driver assistance technologies (lane departure warning, lane keeping assistance, road sign recognition).

The questionnaire was filled by experts from 24 countries, of which 22 are member states and two (Norway and Iceland) are non-EU but their experts are members of EGRIS. In the further text the term "Member States" will include all countries whose experts have replied to the questionnaire. The majority (52.17 %) of experts who filled the questionnaire are employed in the relevant government body (for example Ministry of Transport), while others are representatives of national road authorities.

According to experts' responses, the total length of motorways in the 24 states included in the study is 52,432, of which 44,757 km are on TEN-T network. On the other hand, 159,110 km of road are classified as primary roads, of which 30,178 km are on TEN-T network. It must be noted that classification of roads differs to some extent among countries. For example, Austria for the moment does not have a definition of primary roads in the context of RISM II, while Norway classifies roads into motorways, primary divided rural roads, primary undivided rural roads, other national undivided rural roads and other county undivided rural roads. Also, some countries, such as Estonia, Iceland and Latvia, do not have roads classified as motorways. Since the data for some countries is not exact or is missing, the overall numbers should be considered with caution.

The length of road network according to the classification from the Directive for each country included in this study is presented in Table 3.

Table 3. Length of road network according to the classification from the Directive

Country	**Motorways (km)**	**Motorways on TEN-T (km)**	**Primary roads (km)**	**Primary roads on TEN-T (km)**
Austria	2,258	1,740	NA	NA
Belgium (Wallonia)	874	300	6,944	NA
Bulgaria	800	800	2,900	1,820
Croatia	1,306	1,307	7,097	280
Cyprus	257	257	357	126
Estonia	NA	NA	1,609	1,294
Finland	932	882	12,541	4,337
France	11,700	11,700	9,100	3,200
Germany	13,191	10,350	37,842	345
Hungary	1,233	1,189	7,401[1]	1,258
Iceland	NA	NA	7,850	NA
Italy	7,342	6,413	26,654	3,065
Latvia	NA	NA	1,692	861
Lithuania	430	430	1,321	1,294
Luxembourg	165	91	NA	NA
Norway	374	374	3,906[2]	3,906[2]
Poland	1,713	1,713	2,549	2,549
Portugal	2,985	2,083	579	579
Romania	914	ND	17,740	ND
Slovakia	737[3]	737[3]	3,333	787
Slovenia	617[3]	555[3]	800	43
Spain	ND	ND	ND	ND
Sweden	2,122	1,950	6,301[4]	4,434[4]
The Netherlands	2,482	1,886	594	-
Total	**52,432**	**44,757**	**159,110**	**30,178**

NA – Not applicable; ND – No data
1 – Expressways (379,7 km) + main roads (7.021,3 km); 2 - Primary divided rural roads (333 km) + Primary undivided rural roads (3.573,0 km); 3 – Motorways + expressways; 4 – roads which are nationally financed.

The following section presents results from the questionnaire.

4.1. Current standards and practices related to road markings and road signs

The first part of the questionnaire focuses on the general information regarding current practices and standards for road markings and road signs in each MS and accordingly is divided into two subsections: a) Road markings, and b) Road signs.

4.1.1. Road markings

On motorways and primary roads in 13[4] countries included in this study there is a total of 403,103 km of longitudinal road markings. More than half of all longitudinal markings (54.12%) are on primary roads, while 46% are on motorways. On motorways there is 184,925 km of longitudinal road markings, of which 71,742 km are centre lines and 113,183 km are edge lines. On primary roads there is 66,479 km of centre line markings and 151,699 of edge lines, which in total represents 218,178 km of longitudinal markings. Overall, the total length of edge markings is 264,882 km, while centre lines have the length of 138,222 km.

The total length and percentage share of longitudinal road markings on motorways and primary roads, according to their position (type), is presented in Figure 10.

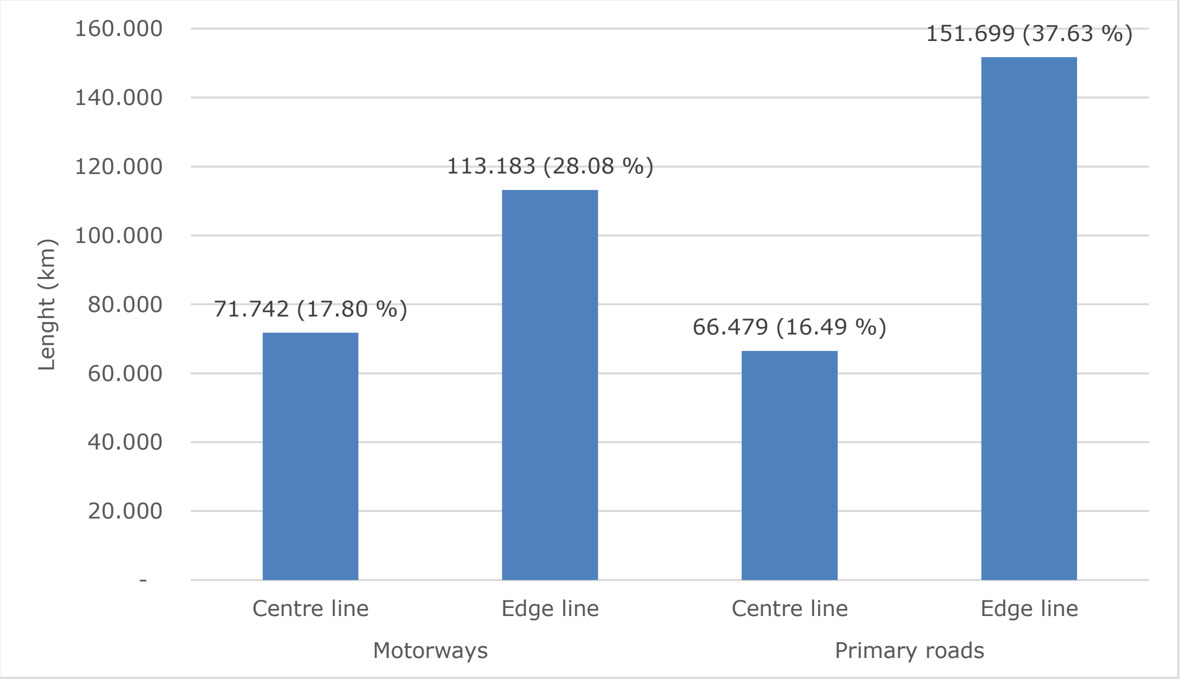


Figure 10. Length and percentage share of longitudinal road markings

Road markings in Member States are based on the Vienna Convention on Road Signs and Signals. White colour is the main colour for permanent road markings both on motorways and primary roads. According to Article 29 "*when permanent road markings are to be modified for a specific period, in particular because of road works or diversions, temporary markings shall be applied in colours different from the colours used for permanent*

[4] Ten countries do not have the data regarding the lenght of road markings

markings". Thus, for temporary markings most countries use yellow (> 90%), while two countries use orange. However, these two countries to some extent use yellow also for permanent markings. Cyprus uses yellow permanent markings on primary roads when accessing urban/build-up areas, while in Norway left edge lines on motorways and centre lines on primary roads are yellow.

Besides the aforementioned colours, in some countries other colours, such as red, green and blue, are used (Figure 11). Red is usually used for marking bicycle lanes, different traffic calming measures or escape lanes painted with a checkerboard pattern. Green is usually used for places reserved for electric vehicles, in dual carriageways in case no barrier is available or on primary roads if the allowed speed is up to 100 km/h or as an additional confirmation of the right direction when entering a motorway. Blue, if applied, is mostly used for parking areas (for disabled people or paid parking). In Italy blue markings are used for card payment lanes, while in Cyprus for bicycle lanes. Seven countries use other colours, although for most of them it was not stated which colour and for what purpose. However, it is important to note that Italy uses alternating yellow and black colour to increase the contrast of the markings.

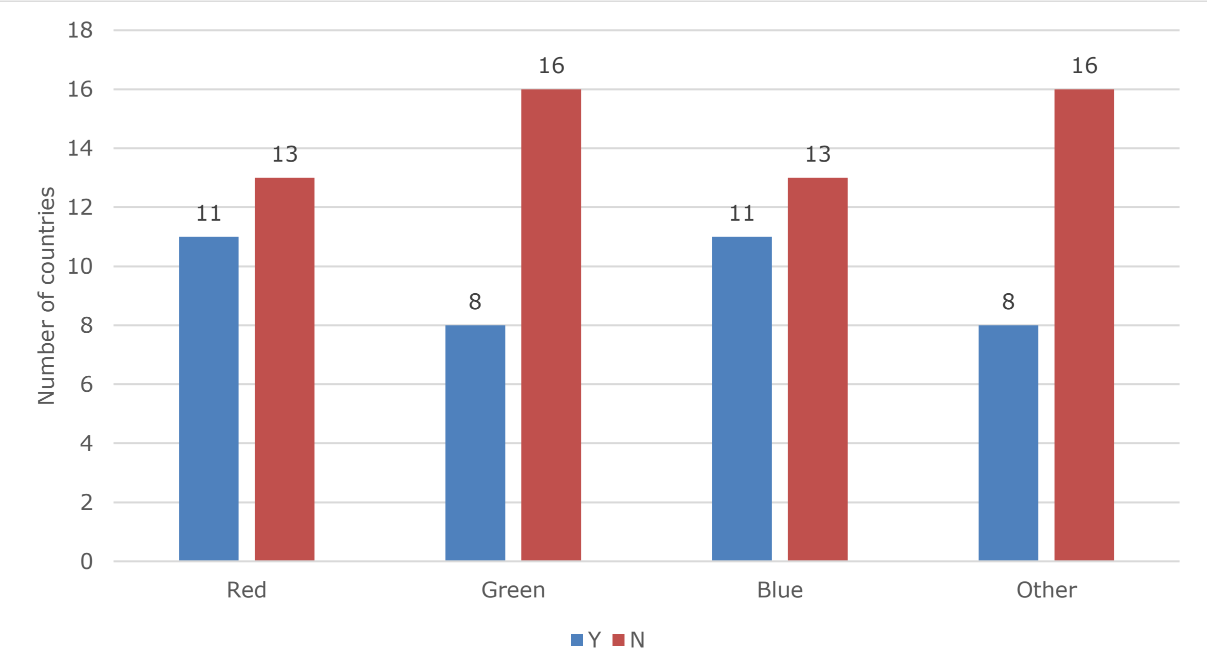
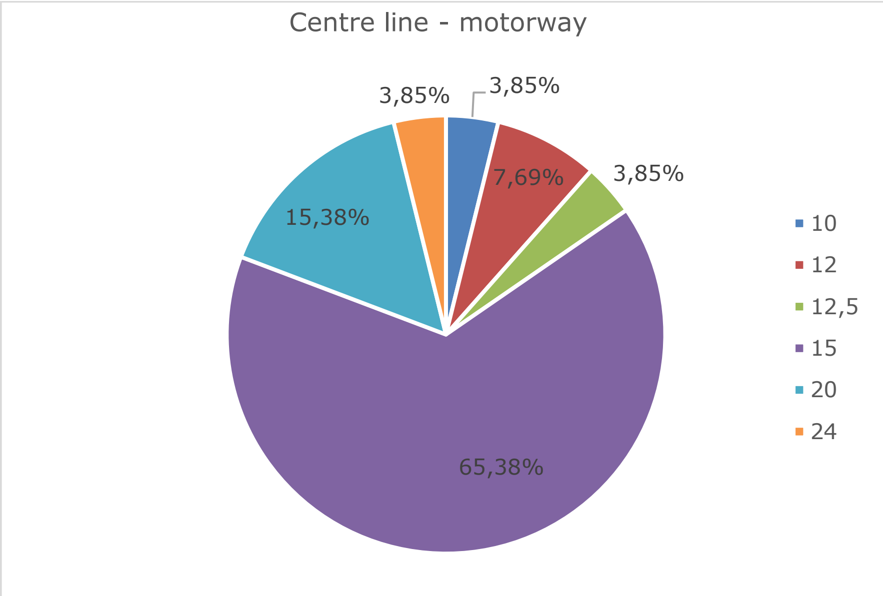


Figure 11. The use of other colours for road markings

When looking at the width of longitudinal road markings, on motorways most of the countries use 15 cm (65.38%) or 20 cm (15.38%) centre lines. The maximal width for centre line is 24 cm and it is used in some cases only in Poland. On the other hand, experts reported that narrower markings, namely 10 cm, 12 cm and 12.5 cm, are also used for centre lines on motorways but only in a few states (15.38%). Ten-centimetre line is used in some cases only in Finland, 12 cm in Poland and Hungary, while 12.5 cm is the standard width for centre lines in Slovakia.

Edge markings on motorways are mostly 20 cm (33.33%) and 30 cm (29.63%) wide. Four countries (14.81%) have edge markings 25 cm wide, one country (3.70%) 24 cm, and two countries (7.41%) 22.5 cm. The minimal reported width for edge markings is 15 cm and it is used to some extent in Hungary and for left edge lines in Germany.

Figure 12 represents the percentage share of reported widths of longitudinal road markings on motorways[5].



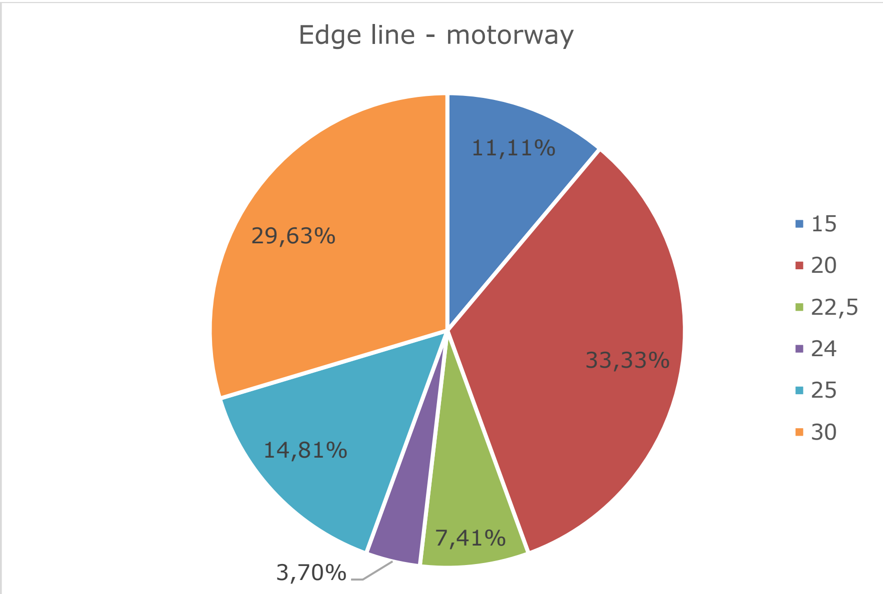


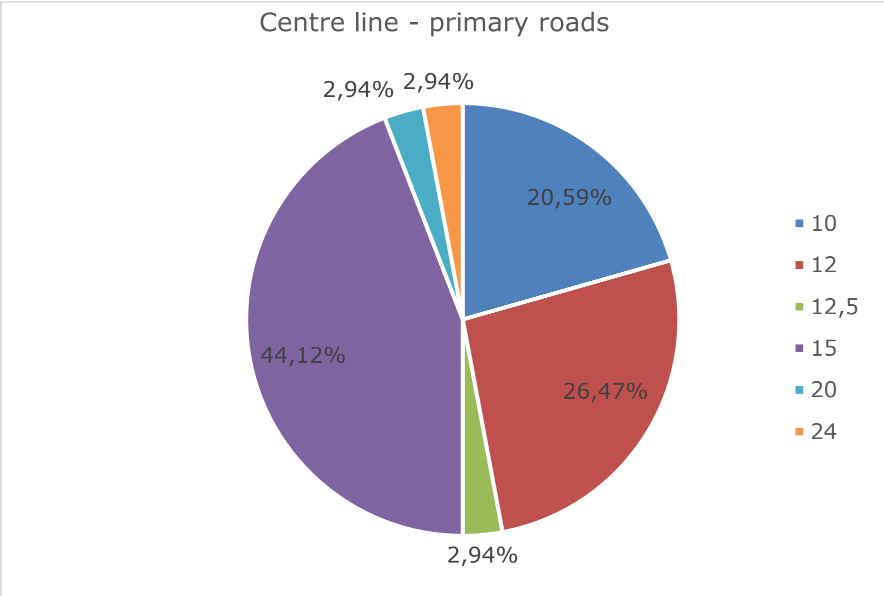
Figure 12. Percentage share of line widths on motorways

In most Member States (44.12%) centre lines on primary roads are 15 cm wide. Eight, i.e., 26.47% of the countries use 12 cm wide centre lines for primary roads, while seven or almost 21% of the countries to some extent use 10 cm wide centre lines. In 2.50% of the countries, the width of 12.5 cm, 20 cm and 24 cm is also used (each width is used in one country). The most common width for edge lines on primary roads is also 15 cm (in 37.50% of the countries), followed by the width of 10 cm (17.50%). Five Member States

[5] In some countries several widths are used.

(12.50%) use the width of 20 cm, five (12.50%) 12 cm, four 25 cm (10.0%), while the width of 18 cm, 24 cm and 30 cm is used only in one country.

The percentage share of reported widths of longitudinal road markings on primary roads is presented in Figure 13[6].



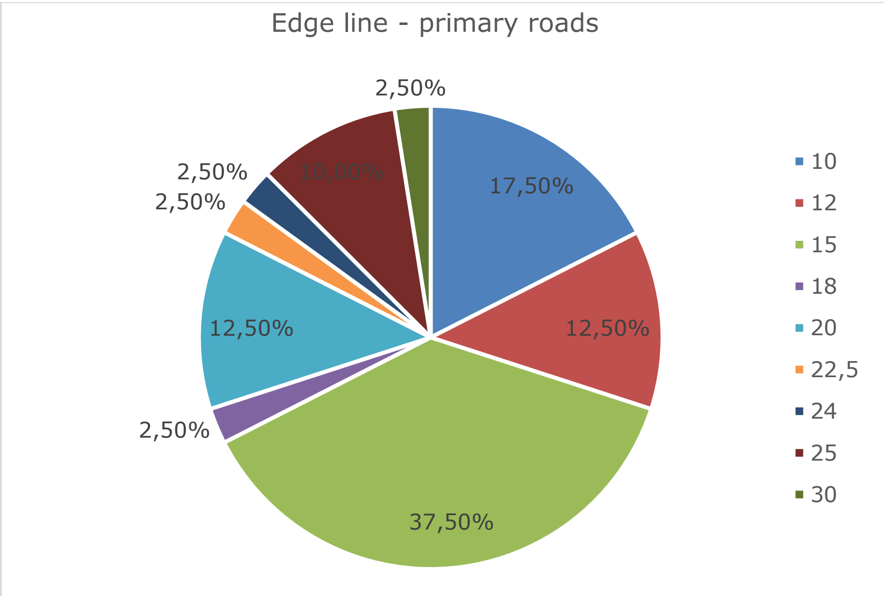


Figure 13. Percentage share of line widths on primary roads

Standard line widths for each country per road type and line position is shown in Table 4[7].

[6] In some countries several widths are used.
[7] If in some countries several widths for the same line are used, theyare presented from the minimal to the maximal one and not by the share of each width in the total lenght of road markings.

Table 4. Standard widths of longitudinal road markings

	Motorways		**Primary roads**	
Country	Centre line	Edge line	Centre line	Edge line
Austria	15	20/30[1]	NA	NA
Belgium (Wallonia)	20	30	15	20
Bulgaria	15	25	10	15
Croatia	20	20	12/15	12/15
Cyprus	20	20	10/15	10/15
Estonia	15[2]	20/30[2]	10/15	10/15/20/30
*Finland**	10/15/20	20/30	10/15	10/15/20
*France***	15	22.5	12/15	18/22.5
*Germany****	15	15/30	12	12/25
Hungary	12/15	15/20	12	15
*Iceland*****	NA	NA	10	10
Italy	15	25	15[3]	12/25[3]
Latvia	NA	NA	10/15/20	10/15/20
Lithuania	15	30	12	25
Luxembourg	15	22.5	12	12
Norway	15	30	10/15	10/15
Poland	12/24	24	12/24	24
Portugal	15	20	12	15
Romania	15	25	15	15
Slovakia	12.5	25	12.5	25
Slovenia	15	20	12/15	12/15
Spain	15	15	15	15
*Sweden******	15	30	15	10/15
The Netherlands	15	20	15	15/20

NA – Not applicable
1 - 30 cm edge line at exits and entries; 2 – Expressways (2+2 and 2+1 lane roads); 3 – On the suburban and main urban and suburban motorways the module is: 25-15-25, on suburban secondary and urban traffic and neighbourhood the module is: 15-12-15, while on local roads (urban and extra-urban) the module is: 12-10-12.
** Centre line can be 30 cm or 40 cm (or 60 cm) on motorway weaving sections. Edge line can be 30 cm or 40 cm on primary roads or motorway weaving sections and even up to 60 cm on motorway weaving sections.*
*** "Non motorway dual carriageways" - centre line: 15cm, edge line: 22,5 cm;*
*** "Single carriageways" - centre line: 12 cm, edge line: 18 cm*
**** Motorways: left edge line 15 or 30 cm, right edge line or dashed right edge line 30 cm, dashed centre line 15 cm. National Roads: edge lines 12 cm, edge lines to separate hard shoulder/bus stops or dashed right edge line 25 cm, dashed centre marking 12 cm.*
***** On the busiest road outside Reykjavík 20 cm edge and 12 cm centre lines are used.*
****** Road markings differ depending on AADT, speed and width of the road.*

The configuration of discontinuous (dashed/broken) lines also differs to some extent among countries. On motorways, most of the countries (five of them) use 6/12/6[8] configuration. The following most common configurations are 3/9/3 and 9/3/9, both used in four countries. Other configurations are also used, such as 5/12/5, 4/12/4, 4/10/4, 4.5/7.5/4.5, 4/8/4, 3.5/11.5/3.5, 3/10/3, 3/4.5/3, 3/1/3 and 1/3/1.

On primary roads, most of the countries (eight of them) use 3/9/3 configuration. Other most common configurations are 9/3/9 and 3/6/3 (three countries in both cases). As in the case of motorways, other configurations are also used, such as 9/3.5/9, 6/9/6, 5/10/5, 4/10/4, 4/8/4, 3/10/3, 3/4.5/3, 2.5/10/2.5 and 1.5/2/1.5.

On intersections on primary roads, most of the countries use 3/3/3 and 1/1/1 configuration. However, other configurations are also present, such as 1.5/1.5/1.5, 1/1.5/1 and 0.5/0.5/0.5.

The summary of the configurations for each state is presented in Table 5.

[8] 6 m line, 12 m spacing, 6 m line

Table 5. Configurations of discontinuous longitudinal lines

	Motorways						**Primary roads**						**Intersections**		
Country	6/12/6	6/6/6	3/6/3	9/3/9	3/9/3	Other	6/12/6	6/6/6	3/6/3	9/3/9	3/9/3	Other	3/3/3	1/1/1	Other
Austria	+	-	-	-	-	6/1.5/6*	-	-	-	-	-	6/9/6	+	-	1.5/1.5/1.5*
Belgium (Wallonia)	-	-	-	-	-	2.5/10/2.5	-	-	-	-	-	2.5/10/2.5	+	-	1/1.5/1
Bulgaria	-	-	+	-	-	4/12/4	-	-	+	-	-	-	-	+	-
Croatia	+	-	-	-	-	-	-	+	-	-	-	-	-	+	-
Cyprus	-	-	+	+	-	-	-	-	+	-	-	-	+	+	-
*Estonia***	-	-	-	-	+	-	-	-	-	-	+	1/3/1	-	+	-
Finland	-	-	-	+	-	-	-	-	-	+	-	-	+	-	-
France	-	-	-	-	-	3/10/3	-	-	-	-	-	3/10/3	-	-	0.5/0.5/0.5
Germany	+	-	-	-	-	-	-	-	-	-	-	4/8/4	+	-	-
Hungary	+	-	-	-	-	-	-	-	-	-	-	4/8/4	-	-	1.5/1.5/1.5
Iceland	-	-	-	+	+	3/1/3; 1/3/1	-	-	-	-	+	-	-	+	-
Italy	-	-	-	-	-	4/7.5/4	-	-	-	-	-	3/4.5/3	-	-	1/1.5/1
Latvia	NA	NA	NA	NA	NA	NA	-	-	-	-	+	-	NA	NA	Not used
Lithuania	-	-	-	-	-	4/12/4	-	-	-	-	+	-	+	-	-
Luxembourg	-	-	-	-	-	3.5/11.5/3.5	-	-	-	-	+	-	+	-	-
Norway	-	-	-	+	-	-	-	-	-	+	-	-	-	+	-
Poland	-	-	-	-	-	4/8/4	-	-	-	-	-	4/8/4	ND	ND	ND
Portugal	-	-	-	-	-	4/10/4	-	-	-	-	-	4/10/4	-	-	3/4/3 1.5/2/1.5
Romania	-	-	-	-	+	-	-	-	+	-	+	-	-	+	-
Slovakia	+	-	-	-	-	-	+	-	-	-	-	-	+	-	-
Slovenia	+	-	-	-	-	-	-	-	-	-	-	5/10/5	-	+	-
Spain	-	-	-	-	-	5/12/5	-	-	-	-	-	9/3.5/9	+	-	-
Sweden	-	-	-	-	+	-	-	-	-	-	+	-	-	+	-
*The Netherlands****	-	-	-	-	+	-	-	-	-	+	+	-	+	+	-

NA – Not applicable; ND – No data
** Motorways: warning line on ramps, bidirectional tunnel - 6/1.5/6, other roads: warning lines 1.5/1.5/1.5*
*** No motorways but values are for expressways (2+2 and 2+1 lane roads), for speed 50 km/h 1/3/1 is used*
**** Primary roads: type 2x2 lanes 3/9/3, type 2x1 lanes 9/3/9*

When looking at the materials used for permanent road markings, on motorways most countries use durable materials, i.e., thermo or cold plastic, as presented in Table 6. The percentages of different types of durable materials (standard or spray thermo or cold plastic) differ among countries. In five countries, the main material are structured road markings[9] (either thermoplastic or cold plastic) with enhanced visibility during wet and rainy conditions (percentage share > 50%). Paint is the main material for road markings on motorways only in four countries. It must be noted that six countries (Bulgaria, Lithuania, Poland, Portugal[10], Slovenia and Spain) do not have available data regarding the used materials for markings, and in three countries (Estonia, Iceland and Latvia) there are no motorways so the questions were not applicable for them. In addition, for some countries the provided percentages are based on estimations and may not represent the "real" situation.

Table 6. Percentage share of used materials for road markings on motorways

	Motorways							
Country	Paint (%)	Standard TP (%)	Spray TP (%)	Standard CP (%)	Spray CP (%)	Structured TP (%)	Structured CP (%)	Tape (%)
Austria	58.6	0.0	0.0	0.0	40.0	0.0	1.4	0.0
Belgium (Wallonia)	4.0	35.0	0.0	5.0	0.0	50.0	1.0	5.0
Bulgaria	ND	ND	ND	ND	ND	ND	ND	ND
Croatia	90.2	2.6	4.6	1.8	0.0	0.7	0.0	0.0
Cyprus	0.0	20.0	80.0	0.0	0.0	0.0	0.0	0.0
Estonia	NA	NA	NA	NA	NA	NA	NA	NA
Finland	0.0	30.0	70.0	0.0	0.0	0.0	0.0	0.0
France	90.0	3.0	0.0	2.0	0.0	0.0	0.0	5.0
Germany	0-10	0-10	0-10	0-10	10-50	0-20	20-80	0-30
Hungary	0.0	26.0	0.0	19.0	5.0	25.0	25.0	0.0
Iceland	NA	NA	NA	NA	NA	NA	NA	NA
Italy	15-20	0.0	80/75[1]	5.0	0-4	0-1	0.0	0.0
Latvia	NA	NA	NA	NA	NA	NA	NA	NA
Lithuania	ND	ND	ND	ND	ND	ND	ND	ND
Luxembourg	70.0	0.0	0.0	0.0	0.0	0.0	5.0	25.0
Norway	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Poland	ND	ND	ND	ND	ND	ND	ND	ND
Portugal	ND	ND	ND	ND	ND	ND	ND	ND
Romania	0.0	40.0	2.0	40.0	2.0	8.0	2.0	0.0
Slovakia	23.3	0.0	0.0	0.0	0.0	3.2	73.5	0.0
Slovenia	ND	ND	ND	ND	ND	ND	ND	ND
Spain	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	0.0	20.0	0.0	0.0	0.0	80.0	0.0	0.0
The Netherlands	0.0	45.0	5.0	15.0	5.0	12.0	12.0	6.0

TP – thermoplastic; CP – cold plastic; NA – Not applicable; ND – No data
1 – first value is for privately managed motorways and second for public motorways

[9] Road marking with a structured surface that does not have areas of road marking of regular dimensions and planeness.
[10] Although there are no accurate data from Portugal, it was written in the comment: *In motorways, standard thermoplastic is used for new markings (first application) but after, for maintenance purposes, paint is used sometimes, especially for edge lines.*

On primary roads, the most common material for permanent road markings is paint. Experts from eight countries stated that 50% or more of the markings are applied in paint. The data regarding used materials on primary roads in seven countries (Bulgaria, Estonia, Latvia, Lithuania, Poland, Portugal and Spain) are not available[11], while Austria does not classify roads as primary roads. As in the case of motorways, for some countries the provided percentages are based on estimations and may not represent the "real" situation. Other countries use different types of durable materials in different percentages, as presented in Table 7.

Table 7. Percentage share of used materials for road markings on primary roads

	Primary roads							
Country	Paint (%)	Standard TP (%)	Spray TP (%)	Standard CP (%)	Spray CP (%)	Structured TP (%)	Structured CP (%)	Tape (%)
Austria	NA	NA	NA	NA	NA	NA	NA	NA
Belgium (Wallonia)	40.0	50.0	5.0	5.0	0.0	5.0	0.0	0.0
Bulgaria	ND	ND	ND	ND	ND	ND	ND	ND
Croatia	95.0	1.0	0.0	3.0	0.0	0.1	0.1	0.0
Cyprus	0.0	20.0	80.0	0.0	0.0	0.0	0.0	0.0
Estonia	ND	ND	ND	ND	ND	ND	ND	ND
Finland	0.0	30.0	70.0	0.0	0.0	0.0	0.0	0.0
France	80.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0
Germany	0-10	10.0	0-10	0-10	20-80	0-20	10-80	0-10
Hungary	59.0	19.0	0.0	10.0	6.0	3.0	3.0	0.0
Iceland	59.5	39.1	1.4	0.0	0.0	0.0	0.0	0.0
Italy	90/85[1]	2.0	2-10	6.0	0-4	1.0	0.0	0.0
Latvia	ND	ND	ND	ND	ND	ND	ND	ND
Lithuania	ND	ND	ND	ND	ND	ND	ND	ND
Luxembourg	0.0	0.0	0.0	0.0	90.0	0.0	10.0	0.0
Norway	10.0	60.0	30.0	0.0	0.0	0.0	0.0	0.0
Poland	ND	ND	ND	ND	ND	ND	ND	ND
Portugal	ND	ND	ND	ND	ND	ND	ND	ND
Romania	70.0	10.0	0.0	10.0	0.0	5.0	5.0	0.0
Slovakia	68.9	0.0	0.0	0.0	0.0	0.0	31.1	0.0
Slovenia	50	ND	ND	ND	ND	ND	ND	ND
Spain	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	5.0	50.0	15.0	0.0	0.0	30.0	0.0	0.0
The Netherlands	0.0	45.0	0.0	10.0	0.0	20.0	20.0	5.0

TP – thermoplastic; CP – cold plastic; NA – Not applicable; ND – No data
1 – first value is for privately managed motorways and second for public motorways

[11] Although there are no accurate data from Estonia and Portugal, the experts stated in the comments that the most common material is thermoplastic.

In most countries profiled markings[12] or rumble strips[13] are used on motorways only for edge lines (41.67%), in 21% of the countries they are used both for centre and edge lines, while in 17% of the countries they are not used at all or are used for other purposes (for example if there is no carriageway barrier). On primary roads in 37% of the countries the aforementioned markings are used for both centre and edge lines. In 17% of the countries they are used only for edge lines, while in 25% of the countries it is not a common practice to use such markings on primary roads, as shown in Figure 14.

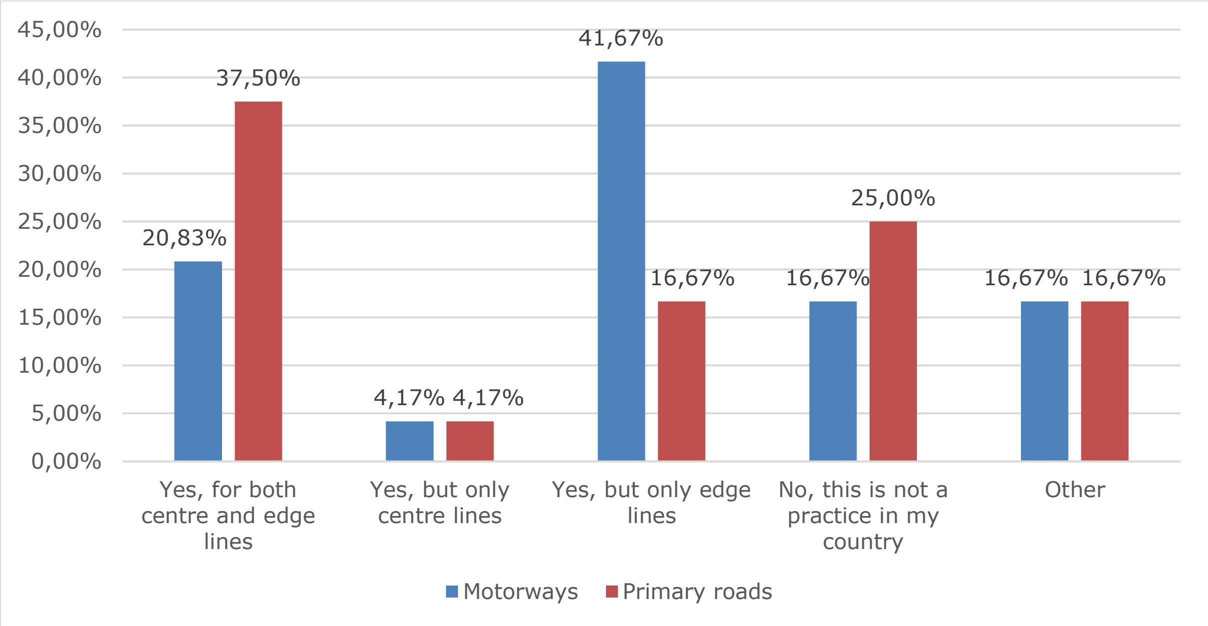


Figure 14. The use of profiled markings or rumble strips on motorways and primary roads

Most of the countries use a combination of national regulations, national guidelines or specifications and standards for defining the technical specifications for road markings. When analysing the percentage share of all answers provided in the questionnaires it can be concluded that most of Member States use national guidelines or specifications (42.70%) and/or national regulations (26.97%). Some countries (25.84%) use international standards, while 4.49% of the countries regulate road markings in other ways (for example through quality control plans which are integrated in road concession contracts or different certificates). The percentage share of ways in which countries regulate road markings is presented in Figure 15.

[12] Profiled road markings are markings which are raised over the road surface

[13] A rumble strip is a raised or corrugated section of a roadway which is designed as a safety feature.

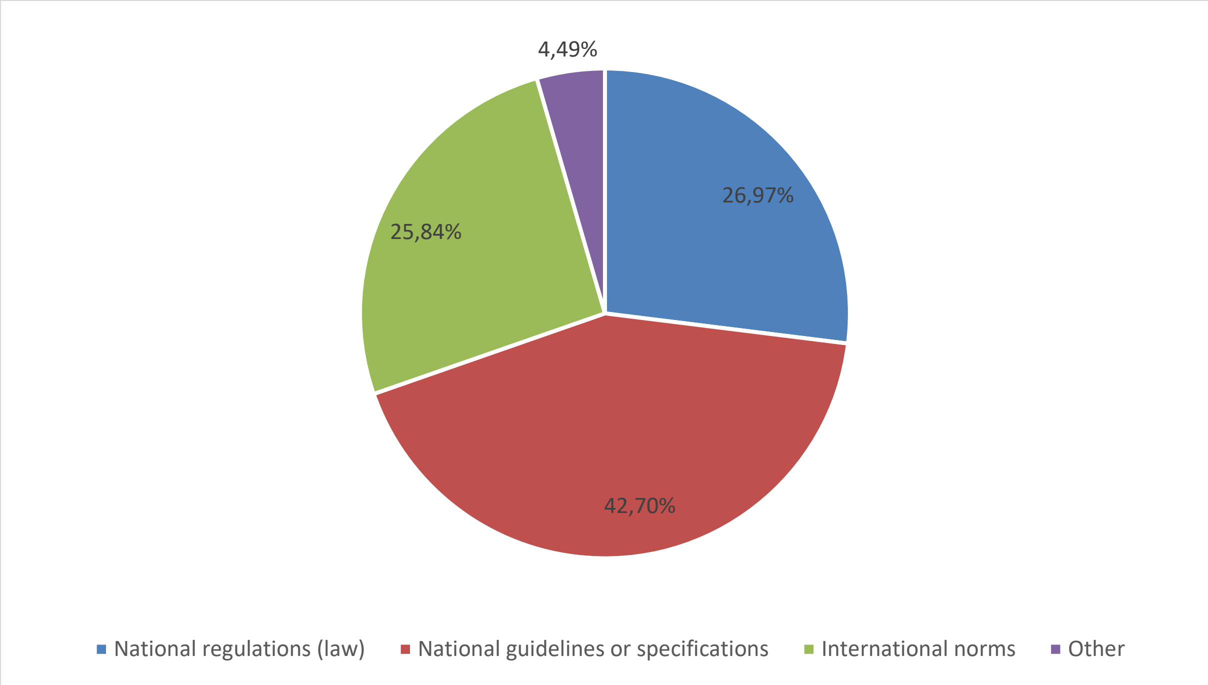


Figure 15. Percentage share of ways in which countries regulate road markings

In most of the countries national regulations, guidelines, specifications or standards regulate the minimal technical requirements, testing procedures, usable materials, service life and durability of materials, quality measures as well as implementation technologies and processes, as shown in Figure 16.

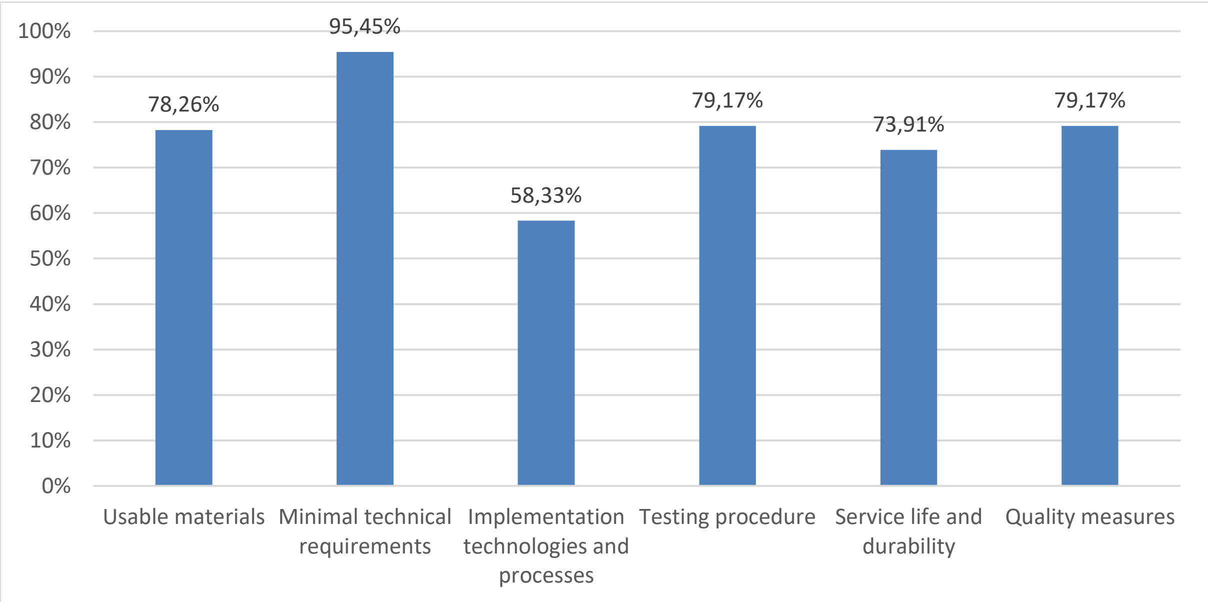


Figure 16. Aspects of road markings regulated by national regulations, guidelines, specifications or standards

Technical requirements for road markings refer to their visibility and skid resistance. From the perspective of this study, the visibility of road markings is the main technical characteristic and, according to EN 1436:2018 [172], it is classified as daytime visibility (Qd), night-time visibility (R_L) and luminance factor (β). Night-time visibility is further divided into the visibility during wetness (RW) and visibility during rain (RR).

Night-time visibility, i.e. retroreflection, represents the quotient of the luminance L of a field of the road marking in the direction of observation by the illuminance $E_\perp$ at the field perpendicular to the direction of the incident light. On the other hand, daytime visibility represents the quotient of the luminance of a field of the road marking in a given direction by the illuminance on the field, while the luminance factor represents the ratio of the luminance of a field of the road marking in a given direction to that of a perfect reflecting diffuser identically illuminated [172].

Minimal daytime visibility of white markings on motorways with asphalt surface is in nine countries defined at 130 mcd/lx/m². This level is minimal both for new markings and for renewed ones. Maximal defined value is 160 mcd/lx/m² (in eight countries), while the minimal one is 100 mcd/lx/m². Four countries do not have defined minimal level of daytime visibility for renewal. Luminance factor varies from 0.3 to 0.8, while chromaticity coordinates (x, y) for dry white road markings are in all countries defined according to EN 1436:2018 (X: 1-0.355, 2-0.305, 3-0.285, 4-0.335; Y: 1-0.355, 2-0.305, 3-0.325, 4-0.375).

On motorways, dry night-time visibility for white markings on asphalt road surfaces is minimum 150 mcd/lx/m² or 300 mcd/lx/m². The maximal defined retroreflection is 300 mcd/lx/m², while minimal value is 100 mcd/lx/m². The minimal retroreflectivity value for renewal (dry conditions) is in most of the countries defined at 100 mcd/lx/m² (six countries) or 150 mcd/lx/m² (four countries). As in the case of daytime visibility, four countries do not have defined minimal level of night-time visibility for renewal.

During conditions of wetness, 50 mcd/lx/m² is the most commonly defined minimal value for new markings, while the most common minimal value for renewal is 35 mcd/lx/m². In both cases (new and renewal), minimal value is 25 mcd/lx/m² and maximal 75 mcd/lx/m². Two countries did not define the minimal level for night-time visibility in the condition of wetness for new markings. Seven Member States did not define this value for markings renewal. For conditions of rain, 14 countries did not define the minimal levels for new markings, while 16 did not define them for the renewal of markings. In Member States which defined the minimal levels for conditions of rain, they are usually 35 mcd/lx/m².

The aforementioned minimal values for each country are presented in Table 8[14].

[14] The values of daytime and night-time visibility shown in the table are measured in milicandelas per lux per square meter (mcd/lx/m²).

Table 8. Minimal values of daytime and night-time visibility (for condition of wetness and rain), luminance factor and skid resistance for road markings on motorways

	Motorways									
Country	Qd – NM	Qd - RE	R_L – NM	R_L - RE	RW – NM	RW - RE	RR – NM	RR - RE	β	SRT
Austria	100/130[1]	100/130[1]	200	100	35	25	35	25	NR	45
Belgium	160/130[1]	160/130[1]	150	150	25	25	25	25	NR	45
Bulgaria	160	130	300	150	50	35	NR	NR	0.5	55
Croatia	160	100	300	150	50	35	NR	NR	0.4	45
Cyprus	130/100[2]	NR	200/150[2]	NR	35	NR	NR	NR	LF6	45
*Estonia**	130	NR	150	NR	35	NR	35	NR	NR	55
Finland	130	130	150	100	NR	NR	NR	NR	0.8	45
France	100/130	NR	150	NR	35	NR	35	NR	NR	45
Germany	160	105[3]	300[4]/200	80[3]	75[4]/50	20[3]	NR	NR	NR	45
Hungary	130	130	200	200	75	75	200	200	0.6	45
Iceland	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Italy	130	100	150	110	50	35	35	25	0.7	45
Latvia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lithuania	130	130	200	200	50	50	NR	NR	NR	45
Luxembourg	160	130	300	150	75	35	NR	NR	NR	55
Norway	130/100[2]	NR	150/100[2]	NR	50	NR	NR	NR	NR	50
Poland	130/160[1]	100/130[1]	250	200	50	35	NR	NR	0.40/0.50[1]	0.45[5]
Portugal	NR	100	200	100	NR	NR	NR	NR	0.3	45
Romania	160	160	300	300	75	75	NR	NR	0.6	45
Slovakia	160	100	300	100	35/50[6]	35/50[6]	35/50[6]	35/50[6]	0.3	45
Slovenia	160	130	300	100	50	35	NR	NR	0.4	45
Spain	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	130	NR	150	NR	35	NR	NR	NR	NR	50
The Netherlands	130	<130	100	<100	35	<35	NR	NR	0.4/0.6	55

NM – new markings; RE – minimal value for renewal; NR – not requested; NA – not applicable; ND – no data
** Expressways (2+2 and 2+1 lane roads)*
1 - first value for asphalt, second for concrete; 2 – first value for white, second for yellow markings; 3 - recommended values according to ZTV M 13 for the renewal of used road markings. ZTV M 13 also defines (higher) values for the end of the warranty period. 4 - first value only for tape; 5 - PFT units; 6 – second value for plastic road markings

On primary roads with asphalt surface, minimal daytime visibility of new white road markings is in most countries 130 mcd/lx/m². Minimal defined level is 100 mcd/lx/m², while maximal is 160 mcd/lx/m². The minimal value for renewal is usually 100 or 130 mcd/lx/m². However, six countries did not define the minimal level of daytime visibility for renewal. Similar to motorways, luminance factor varies from 0.3 to 0.87, while chromaticity coordinates (x, y) for dry white road markings are in all countries defined according to EN 1436:2018 (X: 1-0.355, 2-0.305, 3-0.285, 4-0.335; Y: 1-0.355, 2-0.305, 3-0.325, 4-0.375).

Night-time visibility of new white markings in dry conditions is in majority of the countries defined as 150 mcd/lx/m². Minimal level is 100 mcd/lx/m², while maximal is 300 mcd/lx/m². Several countries such as Croatia, Cyprus, Germany, Lithuania, Luxemburg and Portugal have 200 mcd/lx/m² as the minimal value. The minimal level for renewal (dry conditions) is in most Member States defined at 100 mcd/lx/m². In five countries minimal level is set at 150 mcd/lx/m², while four countries did not define this value. The overall minimal value recommended for the renewal of existing road markings is 80 mcd/lx/m² (Germany).

During wet conditions, the majority of countries defined 50 mcd/lx/m² as the minimal value both for new markings and for renewed ones. The minimal value in both cases is defined at 35 mcd/lx/m², while the maximal value is 75 mcd/lx/m². Four Member States did not define the minimal requirements for new markings in wet conditions. On the other hand, seven Member States did not define the minimal technical requirements in terms of the minimal level for the renewal of road markings. In addition, in Croatia wet visibility is only requested for Type II markings on primary roads.

The minimal level of night-time visibility in rainy conditions is not requested for new markings in 17 Member States and for renewed ones in 18 Member States. In the countries which did define them, the minimal value is usually 35 mcd/lx/m².

The aforementioned minimal values for each country are presented in Table 9[15].

[15] Values of daytime and night-time visibility shown in the table are measured in milicandelas per lux per square meter (mcd/lx/m-²).

Table 9. Minimal values of daytime and night-time visibility (for condition of wetness and rain), luminance factor and skid resistance for road markings on primary roads

					Primary roads					
Country	Qd – NM	Qd - RE	R_L – NM	R_L - RE	RW – NM	RW - RE	RR – NM	RR - RE	β	SRT
Austria	NA	NA	NA	NA	NA	NA	NA	NA	NR	
Belgium	160/130[1]	160/130[1]	150	150	NR	NR	NR	NR	NR	45
Bulgaria	160	130	300	150	50	35	NR	NR	0.5	55
Croatia	130	100	200	100	50[2]	35[2]	NR	NR	0.4	45
Cyprus	130/100[3]	NR	200/150[3]	NR	35	NR	NR	NR	LF6	45
Estonia	130	NR	150	100	35	NR	35	NR	NR	55
Finland	130	130	150	100	NR	NR	NR	NR	0.8	45
France	100/130	NR	150	NR	35	NR	35	NR	NR	45
Germany	130	105[4]	300[5]/200	80[4]	75[5]/50	20[4]	NR	NR	NR	45
Hungary	130	130	150	150	50	50	150	150	0.6	45
Iceland	130	NR	150	100	NR	NR	NR	NR	NR	0.52[6]
Italy	NR	100	NR	150	NR	35	NR	25	0.87	45
Latvia	100	100	150	150	50	50	NR	NR	5	45
Lithuania	130	130	200	200	50	50	NR	NR	NR	45
Luxembourg	160	130	200	100	50	25	NR	NR	NR	45
Norway	130/100[3]	NR	150/100[3]	NR	50	NR	NR	NR	NR	50
Poland	130/160[1]	100/130[1]	250	200	50	35	NR	NR	0.40/0.50[1]	0.45[6]
Portugal	160	100	200	100	50	35	50	35	0.6	45
Romania	160	160	300	300	75	75	NR	NR	0.6	45
Slovakia	160	100	300	100	35/50[7]	35/50[7]	35/50[7]	35/50[7]	0.3	45
Slovenia	160	130	300	100	50	35	NR	NR	0.4	45
Spain	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	130	NR	150	NR	35	35	NR	NR	NR	0.5[6]
The Netherlands	130	<130	100	<100	35	<35	NR	NR	0.4/0.6	55

NM – new markings; RE – minimal value for renewal; NR – not requested; NA – not applicable; ND – no data
1 - first value for asphalt, second for concrete; 2 – only for Type II markings; 3 – first value for white, second for yellow markings; 4 - recommended values according to ZTV M 13 for the renewal of used road markings. ZTV M 13 also defines (higher) values for the end of the warranty period; 5 – first value only for tape; 6 – PFT units; 7 - second value for plastic road markings

In most of the countries the quality assessment of road markings is based on the combination of visual inspection and different measurements (daytime and night-time visibility, SRT etc.). This means that road markings are visually inspected during regular road patrols, while different measurements are conducted periodically – once per year, once every two years or on demand. However, the use of measuring devices is in most countries just an option and is not mandatory. In other words, it is up to the road operator to decide whether they wish to use measuring devices or base their maintenance activities on visual inspection and warranty period.

According to the responses in the questionnaire, the quality of road markings is measured during the guarantee period, and it is mainly related to the visibility of markings since this is the most important characteristic from the safety aspect. Most of the countries use both the static and the dynamic measuring method to assess the visibility of road markings in accordance with EN 1436:2018 [172]. Both methods have advantages and disadvantages. In the static measuring method, a hand-held retroreflectometer is used to measure daytime (Qd) and night-time (R_L) visibility of road markings on specific locations or measuring points. The main disadvantage of the method is that the device itself has a relatively small measuring area and thus does not cover the whole width of the road marking, which may ultimately affect the measurements. In other words, moving the static device by a few centimetres in any direction along the road marking might lead to significant differences in measurements. Also, since the method is based on the point measurements, it does not cover the whole length of the road. Furthermore, the method requires that a measurer is present on the road while conducting measurements which increases safety risks and may disrupt the traffic flow. On the other hand, the dynamic measuring method does not interrupt traffic, it covers 100% of road markings' length thus enabling a more detailed and objective evaluation of their quality, and it is safer for the measuring team. The main disadvantage of the dynamic method is its price, which is significantly higher compared to the static method, and the fact that only night-time (R_L) visibility of road markings can be measured.

Austria is an example of a good monitoring practice, where road markings on motorways are:

- visually inspected minimally once a day for damages or abnormalities during the road patrol
- visually inspected minimally once a year by the head of the sector responsible for road operation and maintenance facility
- measured using handheld devices (skid resistance, daytime and night-time visibility)
- measured using dynamic measuring method (night-time visibility)

4.1.2. Road signs

From the data provided in the questionnaire, it was concluded that the majority of countries (13 of them) do not have data regarding the number of road signs currently placed either on motorways or on primary roads. The total number of road signs in countries which have the necessary data is 280,821 on motorways and 1,109,186 on primary roads. Since these numbers do not represent even half of the states, the extrapolation method was used to calculate the approximate number of road signs. In the first step the calculation of the number of signs per kilometre was done based on the length of the motorway and primary road network and the number of road signs for countries which have the relevant data. In the second step median values of road signs per kilometre were calculated (11 for motorways and 13 for primary roads). The median number was then multiplied by the length of motorway and primary road network for each country in order to estimate the total number of road signs.

Overall, it is estimated that there are 544,202 road signs on motorways and 1,887,269 on primary roads, as shown in Figure 17. However, it must be noted that these figures are just estimations and may not represent the situation accurately.

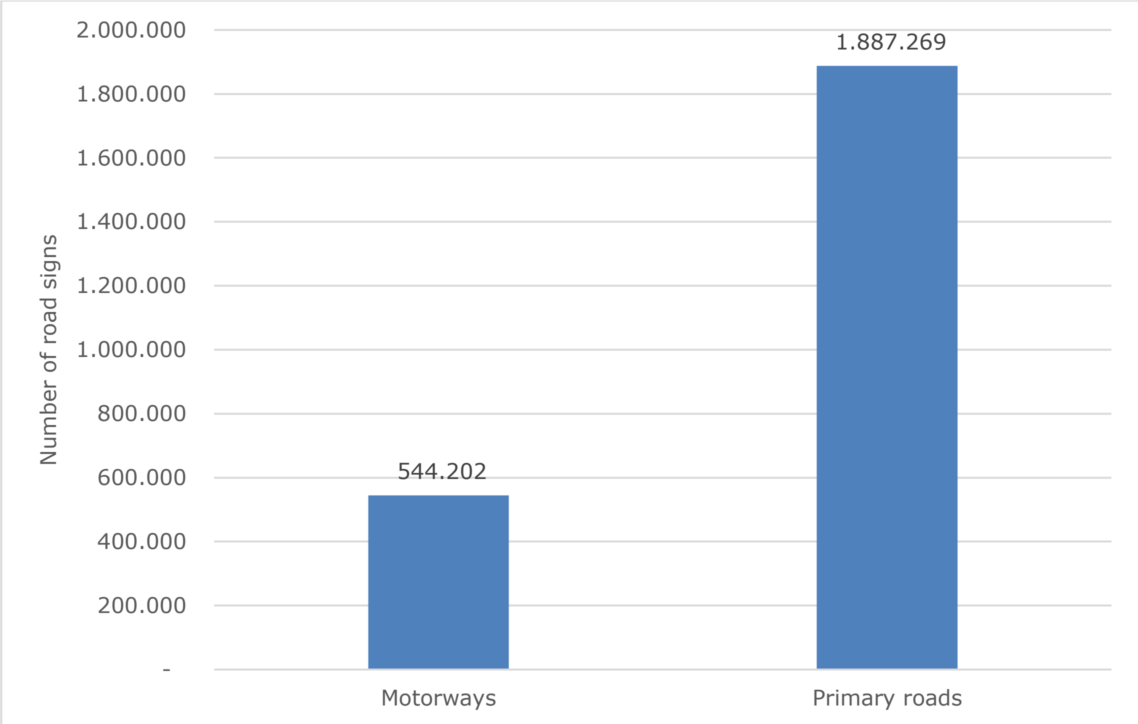


Figure 17. Estimated number of road signs on motorways and primary roads

As in the case of road markings, road signs on motorways and primary roads in all countries are based on the Vienna Convention on Road Signs and Signals. Since advanced driver assistance systems related to road signs detect and recognise mainly prohibition, mandatory and warning, an analysis of sign colours and standard dimensions was done only for those signs.

The majority of the countries (20 in total) use white-red-black combination for warning signs (white background, red outline and black symbol), while four countries (Finland, Iceland, Poland and Sweden) use yellow-red-black combination. The situation is similar for prohibition signs: 21 state uses white-red-black and three states (Finland, Iceland, and Sweden) use yellow-red-black combination. For mandatory signs all countries use blue-white-white combination[16].

When looking at the dimensions, in 60% of the states warning signs on motorways are 120 cm[17]. Other 40% of the states vary in dimensions as follows: 20% - from 110 to

[16] Some states do not use white outline.
[17] Lenght of all sides of triangle.

115 cm; 5% - 100 cm; 10% - 90 cm; 5% - 60 cm. Circle prohibitory and mandatory signs on motorways are in 48% of the states 90 cm in diameter. In 20% of the states they vary in diameter from 70 to 75 cm, in 15% of the states they are 100 cm and in 10% of the states they are ≥ 120 cm. Only Portugal and Finland have unique dimensions, 115 cm and 64 cm respectively.

On primary roads, warning signs are usually (68%) 90 cm. In Iceland and Lithuania, they are 70 cm and in Estonia and Slovakia they are 60 cm. Larger dimensions are also present, for example 100 cm in France, 105 cm in Poland and 120 cm in Romania. Circle prohibitory and mandatory signs on the same roads are mostly 60 cm (in 35% of the countries). In five countries (25%) the dimensions are from 70 to 75 cm, in four (20%) they are 90 cm, while in three (15%) they are from 80 to 85 cm. Like for the motorways, Finland has a unique dimension of 64 cm.

Dimensions of warning, prohibitory and mandatory signs per each country and road type are presented in Table 10.

Table 10. Standard dimensions of warning, prohibitory and mandatory signs for each country and road type

	Motorways		**Primary roads**	
Country	Warning	Prohibitory and mandatory	Warning	Prohibitory and mandatory
Austria	126	75	NA	NA
Belgium	110	90	90	40*
Bulgaria	120	90	90	70
Croatia	120	90	90	60
Cyprus	120	120	90	90
Estonia	NA	NA	60	60
Finland	90	64	90	64
France	150	125	100	85
Germany	126	75	90	60
Hungary	100	90	90	75
Iceland	90	70	70	60
Italy	120	90	90	60
Latvia	NA	NA	90	70
Lithuania	120	90	70	60
Luxembourg	110	90	90	70
Norway	120	100	90	80
Poland	120	100	105	90
Portugal	115	115	90	90
Romania	150	90	120	90
Slovakia	60	75	60	75
Slovenia	120	90	90	60
Spain	ND	ND	ND	ND
Sweden	120	90	90	60
The Netherlands	110	100	90	80

**Dimensions of circle prohibitory and mandatory signs differ according to the speed limit: min. 70 cm for speed ≥ 50 ≤ 90, min. 60 cm for speed ≥ 30 ≤ 50 km/h and min. 40 cm for speed ≤ 30 km/h.*
NA – not applicable
ND – not data

On motorways, the majority of road signs are produced from Class II retroreflective material. Some countries, such as Luxemburg, Romania or Netherlands on motorways use only Class III signs which have the highest retroreflectivity properties. On the other hand, from 5% to 20% of signs on motorways are made of Class I material which is characterised with the lowest retroreflectivity levels. On primary roads the majority of countries have Class II signs. Three countries (Croatia, Iceland and Norway) mostly use Class I. From 5% to 40% of the signs, depending on the country, are produced from Class III material. The Netherlands is the exception which, as on motorways, uses only Class III material for signs on primary roads.

The percentage share of each material on motorways and primary roads for each country is shown in Table 11. Since the actual number of road signs is not known in the majority of Member States, it must be noted that the percentages are mostly based on the experts' estimations.

Table 11. Estimated percentage share of different retroreflective materials for each country and road type

	Motorways			**Primary roads**		
Country	Class I	Class II	Class III	Class I	Class II	Class III
Austria	0.0%	10%	90%	NA	NA	NA
Belgium	0.0%	75.0%	25.0%	20.0%	75.0%	5.0%
Bulgaria	ND	ND	ND	ND	ND	ND
Croatia	8.3%	87.5%	4.2%	62.0%	30.0%	8.0%
Cyprus	ND	ND	ND	ND	ND	ND
Estonia	ND	ND	ND	ND	ND	ND
Finland	0.0%	80.0%	20.0%	10.0%	70.0%	20.0%
France	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%
Germany	5-10%	60-80%	20-40%	<5%	90-95%	5-10%
Hungary	0.0%	80.0%	20.0%	0.0%	95.0%	5.0%
Iceland	NA	NA	NA	95.0%	4.5%	0.5%
Italy	20.0%	10-50%	30-90%		60%	40%
Latvia	NA	NA	NA	NA	NA	NA
Lithuania	ND	ND	ND	ND	ND	ND
Luxembourg	0.0%	0.0%	100.0%	0.0%	70.0%	30.0%
Norway	20.0%	70.0%	10.0%	60.0%	30.0%	10.0%
Poland	ND	ND	ND	ND	ND	ND
Portugal	ND	ND	ND	ND	ND	ND
Romania	0.0%	0.0%	100.0%	0.0%	80.0%	20.0%
Slovakia	0.0%	70.0%	30.0%	0.0%	70.0%	30.0%
Slovenia	0.0%	95.0%	5.0%	0.0%	95.0%	5.0%
Spain	ND	ND	ND	ND	ND	ND
Sweden	ND	ND	ND	ND	ND	ND
The Netherlands	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%

NA – not applicable; ND – no data

As for road markings, most of the countries use a combination of national regulations, national guidelines or specifications and standards for defining the technical specifications for road signs. Furthermore, national regulations, guidelines, specifications or standards in most of the countries regulate the minimal technical requirements, testing procedures, usable materials, service life and durability of materials, quality measures as well as implementation technologies and processes as shown in Figure 18.

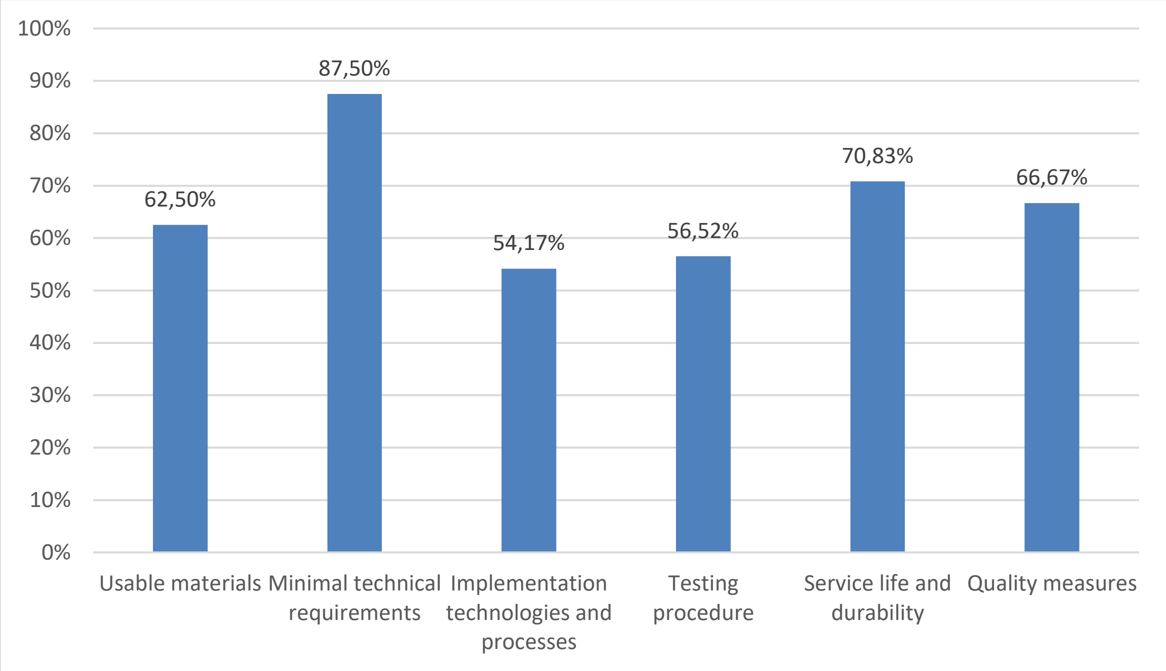


Figure 18. Aspects of road signs regulated by national regulations, guidelines, specifications or standards

In all countries the quality control of road signs is conducted using visual inspection (subjective evaluation). In 67% of the countries, in addition to visual inspection, the quality of road signs is assessed based on measurements of different properties (mainly retroreflection and colorimetry). However, such measurements are not mandatory in most countries, and it is up to the road operator to decide whether they wish to use them. The measurement practices also differ to some extent among countries. In some countries visibility is checked yearly on random sections, in others this is done after the installation and before the warranty expires, in some the visual inspection confirms or rejects subjective conclusions of the inspector, while in others it is done on demand. However, most of the Member States base the quality assessment of road signs on visual inspection.

4.2. The effect of the weather and atmospheric phenomena and traffic on road markings and road signs

This section presents data regarding the effect of weather and atmospheric phenomena and traffic on road markings and road signs on the Trans-European Transport Network (TEN-T), motorways and other primary roads in EU Member States.

a) The effect of the weather and atmospheric phenomena on road markings and road signs

The climate in Europe is diverse and according to the Köppen Climate Classification Map, Europe has several climate types: Class B - Dry (Arid and Semiarid) climate, Class C - Temperate (Mesothermal) climate, Class D - Continental (Microthermal) climate and Class E - Polar and Alpine climate.

Class B climates are characterised by potential evaporation and transpiration exceeding precipitation. These climates are usually found in areas from 20 - 35° north and south of the equator and in large continental regions of the mid-latitudes often surrounded by mountains. Class C climates have an average monthly temperature of 10 °C or more in the spring/summer months (April to September in northern hemisphere), and an average monthly temperature lower than −3 °C in the fall/winter months. Class D climates have an average temperature above 10 °C in their warmest months, and the coldest month average below −3 °C (or 0 °C in some areas). Class D usually occur in the continental interior and on the upper east coasts, normally north of 40°N. In the Southern Hemisphere, group D climates are extremely rare due to smaller land masses in the middle latitudes and the almost complete absence of land at 40–60°S, existing only in some highland locations. Class E is characterised by a lack of warm summers and every month usually has an average temperature of less than 10 °C.

Climate types are further divided into subtypes. In most of Europe three main climate subtypes are dominant: temperate oceanic, humid continental mild summer (wet all year round) and hot-summer Mediterranean. Temperate oceanic climate has average temperatures below 22 °C (all months), while the temperature in the coldest month is averaging above 0 °C. Also, in this climate type there is no significant precipitation difference between seasons. In the humid continental mild summer climate (wet all year round) the coldest month is averaging below 0 °C, all-year average temperatures are below 22 °C, while at least four months in this climate subtype are averaging above 10 °C. There is no significant precipitation difference between seasons in this climate subtype. The hot-summer Mediterranean climate is in the polar front region in winter, and thus has moderate temperatures and changeable, rainy weather. Summers are hot and dry, except in the immediate coastal areas, where they are milder due to the nearby presence of cold ocean currents that may bring fog but prevent rain.

Except mentioned main subtypes, other climate subtypes are also present, such as:

- Warm-Summer Mediterranean Climate – The coldest month is averaging above 0 °C, all-year average is below 22 °C, and at least four months are averaging above 10 °C. Also, at least three times as much precipitation in the wettest month of winter as in the driest month of summer (the driest month of summer receives less than 30 mm).
- Cold Semi-Arid Climate - At least one month is averaging below 0 °C.
- Humid Subtropical Climate – The coldest month is averaging above 0 °C, while at least one month has an average temperature above 22 °C and at least four months are averaging above 10 °C. There is no significant precipitation difference between seasons.
- Tundra Climate – The warmest month has an average temperature from 0 to 10 °C.
- Humid Continental Hot Summers with Year Round Precipitation – The coldest month is averaging below 0 °C, while at least one month has an average temperature above 22 °C and at least four months are averaging above 10 °C. There is no significant precipitation difference between seasons.

- Subarctic with Cool Summers and Year Round Rainfall – The coldest month is averaging below 0 °C, while 1–3 months have an average above 10 °C. There is no significant precipitation difference between seasons.

The experts' comments and descriptions of the climate in their countries are presented in Table 13.

Table 12. Representation of different climate regions/zones and their characteristics in every EU country

Country	Climate conditions in the EU countries
Austria	The main area of Austria is alpine region with heavy and moderate snow (part of lower Austria, Burgenland and Vienna).
Belgium	Climate type is "temperate oceanic". Climate zone C2 (Cfb) from the Koppen classification (EN 1824 - Annex A).
Bulgaria	The climate is generally continental, with cold winters and warm to hot summers; it is slightly milder along the coast of the Black Sea, and of course colder in the hills and mountains.
Croatia	-
Cyprus	Cyprus has a subtropical (Mediterranean) climate with very little variation across the country. The climate is characterised by very mild winters and warm to hot summers. Snow is possible only in the Troodos mountains in the central part of the island. Throughout the island there are high humidity levels that often affect visibility especially during early morning hours.
Estonia	In winter snow with -10 to -20 °C, in summer +15 to +25 °C. Autumn rainy.
Finland	The whole of Finland normally has four seasons. However, the length of seasons varies a lot according to latitude.
France	Climate conditions are very different depending on the area. The French territory is divided into five zones according to the annual average of days of snow and ice. The two zones with the highest average are grouped together below in "heavy snow".
Germany	Germany belongs to the cool temperate climate zone and is located in the transition area between the maritime climate of Western Europe and the continental climate of Eastern Europe. In Germany, continentality increases from northwest to southeast. The degree of continentality of a place is described by the so-called continentality index. Individual characteristics (precipitation, fog, snowfall, warm periods) can occur similarly everywhere. Depending on the location, these characteristics occur with different frequency. Here are a few examples: in individual cases, snow depths of 1 m already occurred in the coastal regions; they occur more frequently in the German mountainous regions. Drought occurs more often in the eastern inland because there the continentality is already more pronounced compared to the seaside. Nevertheless, other regions can also be affected by drought. Areas near water bodies are more often affected by fog than those without water bodies. However, fog can also affect all regions.
Hungary	There are no different climate zones within Hungary. The country has a typical continental climate with warm summers and relatively cold winters. Rain is normal in every season. We usually have fog in autumn and snow in some winter days.
Iceland	We have many highland roads with heavy snow during the winter.

Italy	Northern Italy and Apennine ridge: continental climate (harsh winters characterised by rain, including snow). Northern Italy plains: constant fog phenomena. Central-Southern Italy, Central-Southern Islands: Mediterranean climate (hot summers with constant heat).
Latvia	-
Lithuania	Lithuania is in the cool temperature climate zone. Mild summer (average air temp. is 17 °C) and winter (average air temp. is -5 °C) that usually lasts for 3 to 4 months with light or moderate snow (last few seasons were an exception with almost no snow). Heavy rains in the summer season is common here. Fog is very common in autumn and spring. Road equipment (road markings, road signs) is affected by temperature ranging from -20 °C to +50 °C.
Luxembourg	Luxembourg has an oceanic climate, marked by high precipitation, particularly in late summer. The summers are warm and winters are cool.
Norway	In Norway there are different climate zones, with heavy winter and snow conditions in the north of the country, while more moderate conditions in the south. However, there is a lot of rain in the west of the country and in the south.
Poland	-
Portugal	The climate in Portugal is Mediterranean. Portugal is one of the mildest European countries: the average annual temperature on the mainland varies from 4 °C in the mountainous north interior to 18 °C in the south. Summers are mild in the northern highlands of the country and in the northern and central coastal regions. Autumn and winter are typically windy, rainy and cool, being colder in the northern and central districts of the country, where negative temperatures occur during the coldest months. However, in the southernmost cities of Portugal, temperatures only occasionally drop below 0 °C. Normally, the spring and summer months are sunny, and temperatures are high during the dry months of July and August and can occasionally exceed 40 °C in extreme days. The average annual total precipitation varies from just over 3000 mm in the northern mountains to less than 600 mm in the southern parts. The country has around 2500–3200 hours of sunshine per year, and an average of 4–6 hours in winter and 10–12 hours in summer, with higher values in the southeast and lower in the northwest. Snow occurs regularly in four districts in the north of the country and decreases its occurrence towards the south, until it does not exist in most of the Algarve. In winter, temperatures below -10 °C and snowfall occur with some frequency in restricted spots, and it can snow from October to May in these places.
Romania	Temperate continental weather.
Slovakia	Northern temperature climate zone with alternation of four seasons.
Spain	-
Sweden	In Sweden there are different climate zones involving snow, cold and frost.
The Netherlands	There are no climate regions in the Netherlands. It has a sea climate (four distinct seasons with frost and snow in winter and hot days in summer, and a relatively high amount of yearly rainfall).

When asked about the impact of weather conditions on road markings, the majority of experts (65%) stated that based on the information they have at hand, weather conditions significantly affect the quality, durability and visibility of road markings.

Thirteen percent of experts were undecided, while around 21% of them did not agree with the aforementioned statement, as seen from Figure 19.

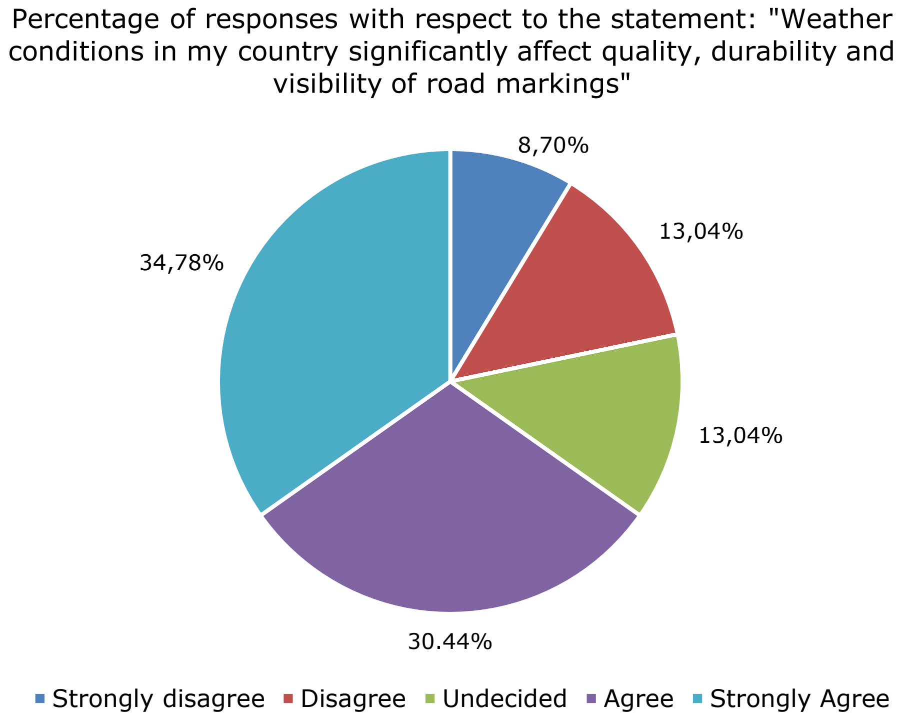


Figure 19. Representation of the responses regarding weather conditions and its effect on quality, durability and visibility of road markings

During winter season, in most of the countries there is a certain level of snow, at least in some areas, and snowploughs are used for road maintenance. Most of the experts (56%) stated that snowploughs damage road markings at least partially (Figure 20). The level of damage depends on the number of snowplough passages and on the practice used for snowploughing. For example, it is stated that in France road markings are particularly damaged in areas with “heavy snow”, in Spain and Portugal this is the case only for “specific mountain roads”, in Austria “road markings may not be totally or partially damaged, but their quality parameters (retroreflection and similar) may not be fulfilled any more”, while in the Netherlands snowploughs do not have such a negative effect since they “do not have metal components on the shovel”.

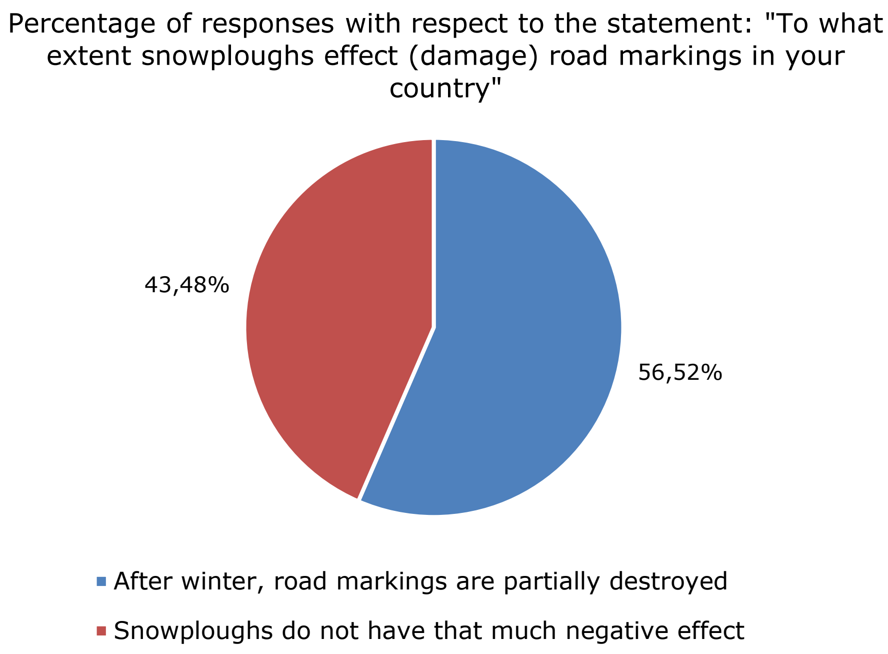


Figure 20. Experts' opinion on the impact of snowploughs on road markings

Regarding the impact of snowploughs on road signs, most of the countries claimed that they do not have such a negative impact (65%) on road signs (Figure 21). However, in some Member States, snow from snowploughs may damage road signs (at least partially). This is mainly dependent on the speed of snow clearing and snow consistency. In other words, wet and heavy snow at too high a clearing speed can lead to the deformation of road signs.

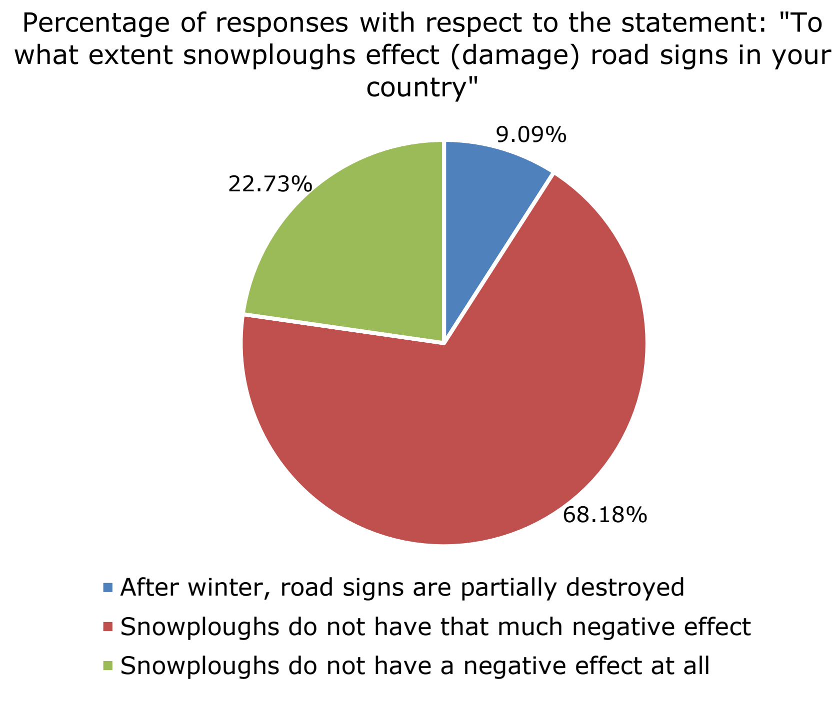


Figure 21. Experts' opinion on the impact of snowploughs on road signs

In the majority of the countries (70%) there is no standard practice of using specific road marking materials due to low average temperatures in the area where the road is located. When it comes to wet and rainy conditions, in 30% of Member States it is standard practice to use road marking materials with enhanced visibility in wet or rainy conditions. In 39% of the countries such markings are used occasionally, while in 26% this is not a standard practice. However, from Tables 6 and 7, it can be concluded that, at least on motorways, most Member States use durable materials (i.e. thermo or cold plastic) and that in five countries structured road markings (either thermoplastic or cold plastic) with enhanced visibility during wet and rainy conditions are the main material (percentage share > 50%).

According to the statements of experts, the use of markings with enhanced visibility during wet and rainy conditions positively affect the overall road safety. Experts stated that in their opinion such materials increase the visibility of markings during diverse weather and visibility conditions, decrease road accidents, increase "comfort" in drivers while driving and provide longer service life of road markings (Figure 22). Although the experts stated that they assume that such materials have a positive effect on the visibility of road markings during night-time and thus on road safety compared to "regular" materials, it is highlighted that more research is needed to validate this opinion.

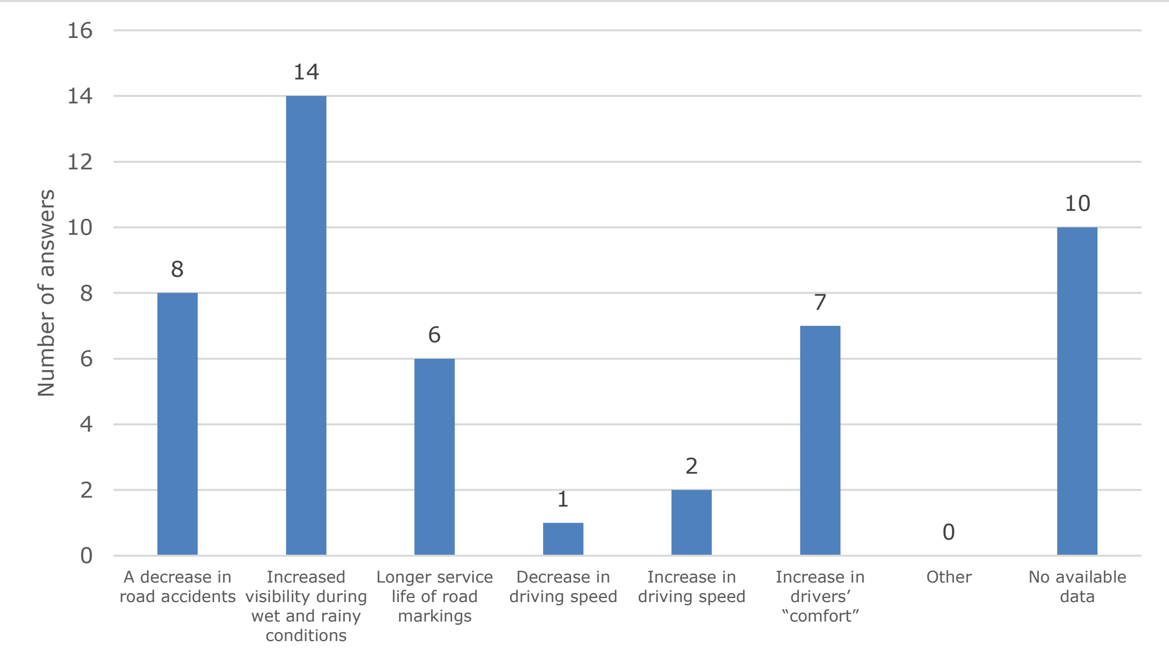


Figure 22. Experts' opinion on the effect of road markings with enhanced visibility in wet and rainy conditions

Like for areas with low temperatures, Member States also do not have the practice to use special road marking materials in areas with high average temperatures and sunny weather[18].

Hight temperatures and solar radiation may affect road sign quality to some extent. This effect is mainly related to the degradation of colours on signs. As seen in Figure 23, 35% of the experts stated that solar radiation has a medium effect on road signs and

[18] It is up to the road operator to decide whether they wish to use a product with a high maximum temperature of use.

their quality, while 22% stated it has a significant effect. On the other hand, 30% of the experts stated that solar radiation has a small impact.

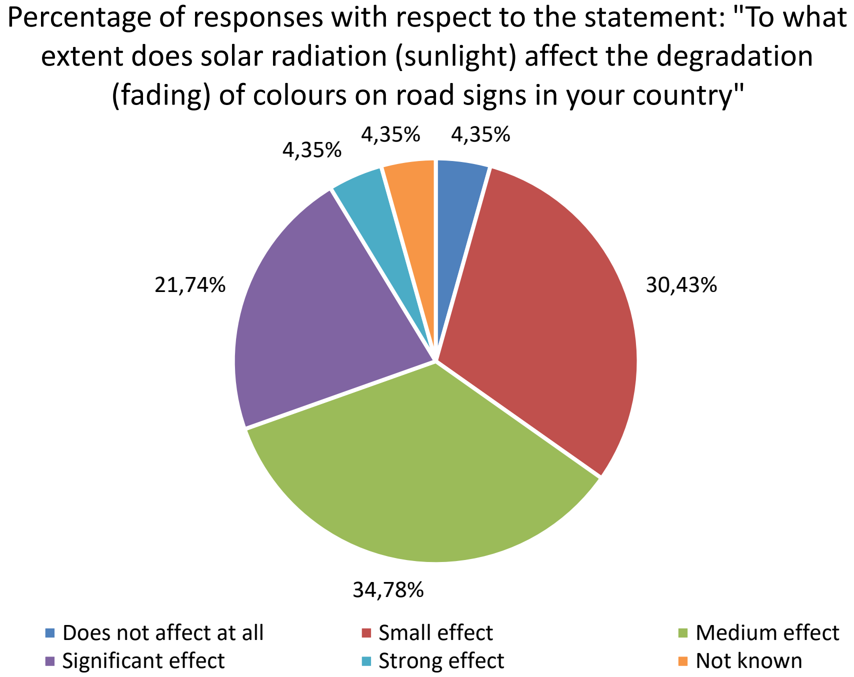


Figure 23. Representation of the responses regarding the effect of sunlight on degradation of road sign colours

a) The effect of traffic on road markings and road signs

As in the case of weather and atmospheric conditions, most of the experts stated that traffic conditions significantly affect the quality, durability and visibility of road markings (Figure 24). However, 30% of them do not agree with the aforementioned statement, while 17% are undecided.

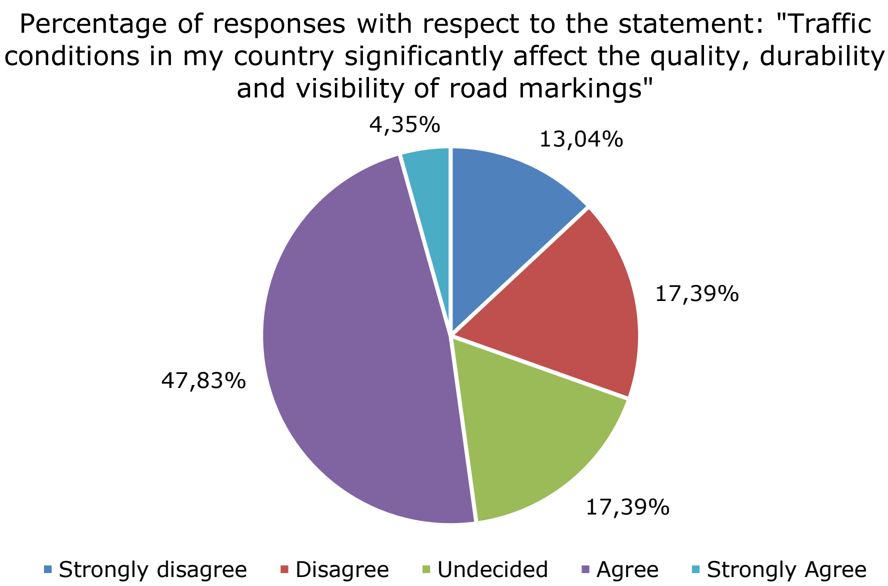


Figure 24. Representation of the responses regarding weather conditions and their effect on quality, durability and visibility of road signs

Also, experts indicate that traffic (AADT[19]) has a different impact on road markings, depending on their location on the road. Left edge longitudinal markings are crossed very seldom, especially by heavy vehicles, compared to middle and right edge lines. Thus, left edge markings are the least affected by traffic, while middle and right edge markings are more significantly affected (Figure 25).

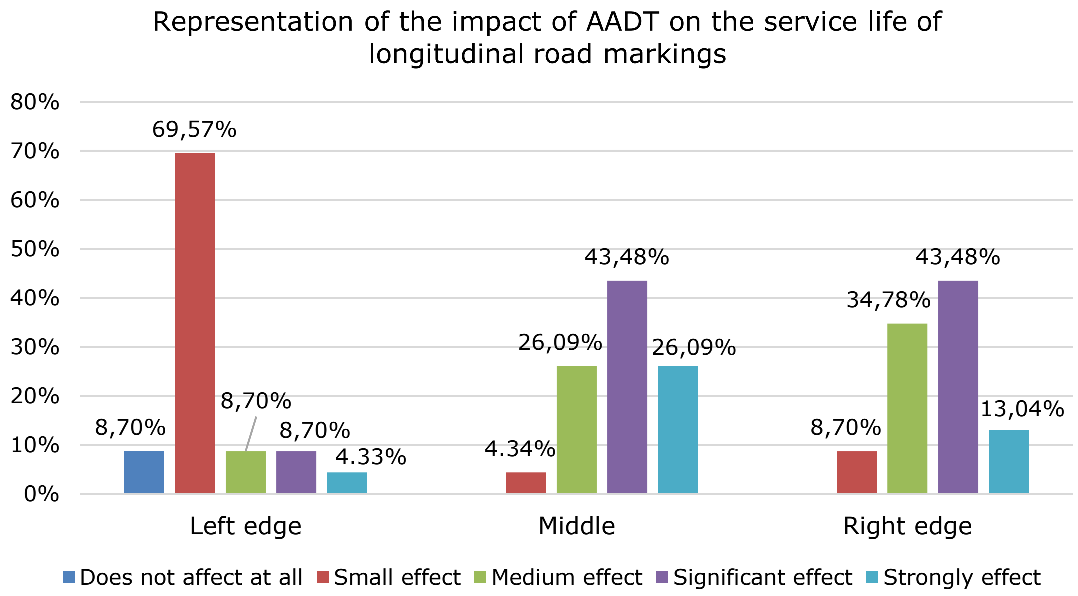


Figure 25. Representation of the impact of AADT on the service life of longitudinal left edge, middle and right edge road markings

AADT has a more significant impact on transverse road markings due to their position on the road (Figure 26).

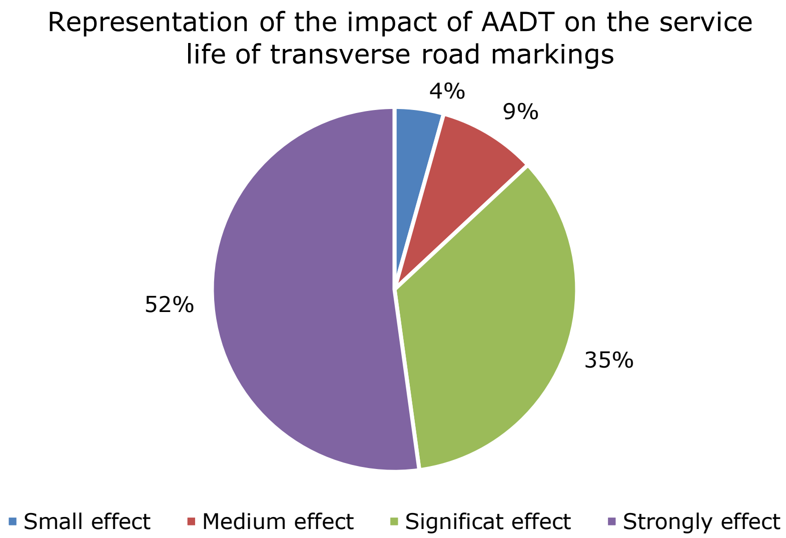


Figure 26. Representation of the impact of AADT on the service life of transverse road markings

[19] Annual Average Daily Traffic

Most of the Member States (61%) have a standard practice to select specific road marking materials for roads with demanding traffic conditions (Figure 27). The states use different approaches. While in demanding traffic conditions some countries use standard cold plastic (for example Austria and Luxembourg), others use thermoplastic (Belgium, Estonia, Finland Hungary and Italy). In Germany on motorways with very high traffic loads it is a standard practice to use durable materials like, e.g., thick layered road markings or structured road markings (agglomerates). In some cases, where it is not possible to disturb traffic at short intervals in order to maintain road markings, very durable materials (tapes) may be also used, although it is not a standard practice. In 40% of the countries however, there is no standard practice in place, and it is usually up to the road operator to decide whether they wish to use a product with a high roll-over class (class P5 or P6) according to the EN 1824.

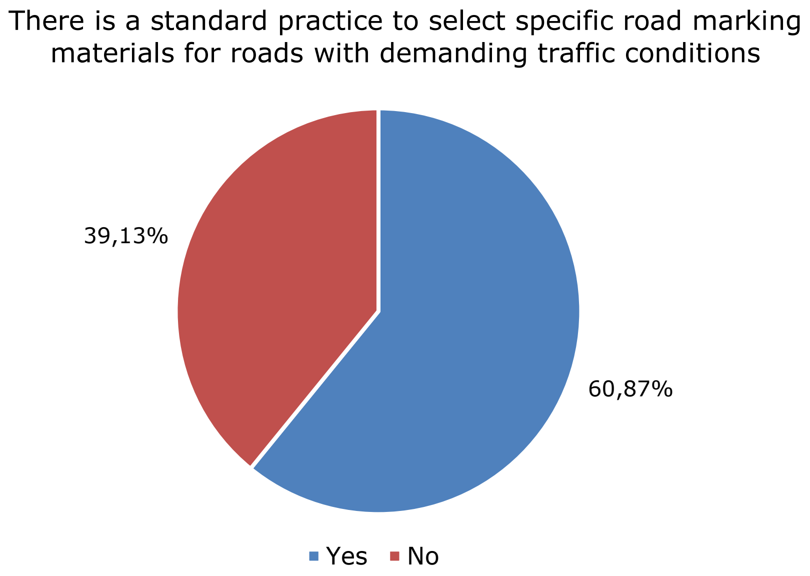


Figure 27. Representation of practices regarding usage of specific road marking materials for roads with demanding traffic conditions

When looking at the impact of traffic on the service life of road signs, experts stated that in their opinion AADT does not affect road signs at all or if it does then it has a small effect. Road signs placed on the left and right side of the roadway are, in the experts' opinion, a little bit more affected by traffic than those placed above the roadway (Figure 28).

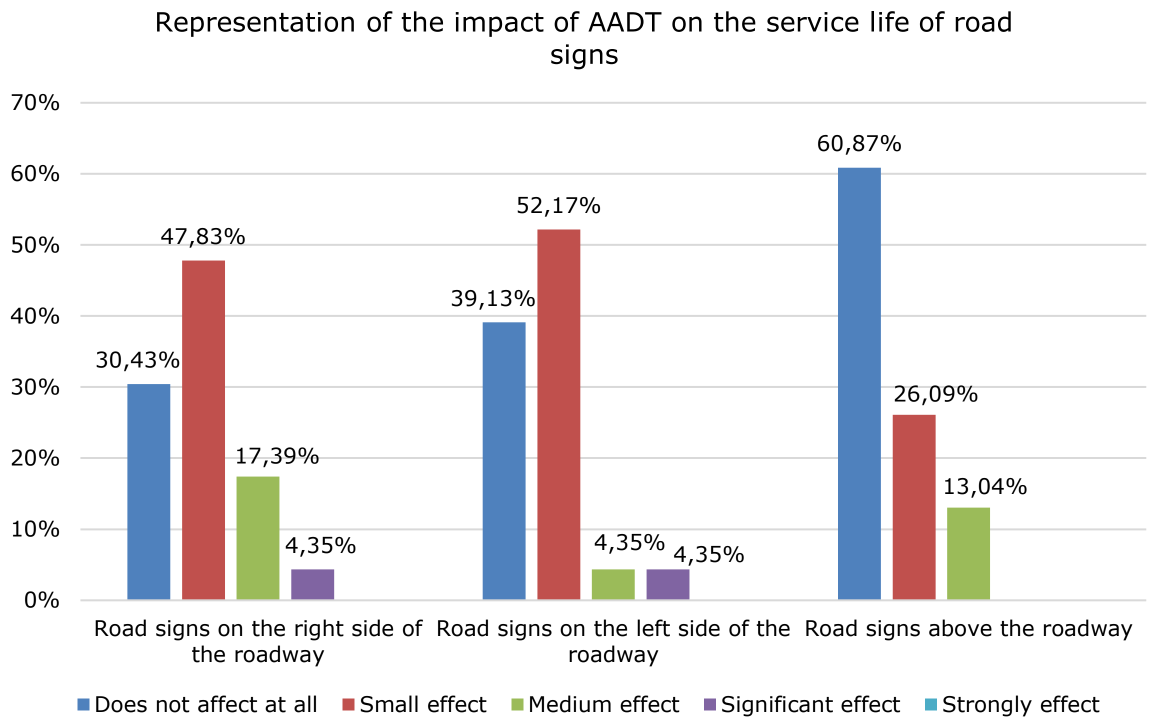


Figure 28. Representation of the extent to which AADT affects the service life of road signs placed on the right and left side of the roadway, and above the roadway

4.3. Maintenance practices for road markings and road signs

This section provides basic information about the maintenance practices of road markings and road signs on the Trans-European Transport Network (TEN-T), motorways and other primary roads in MS. It must be noted that due to the lack of accurate data, only rough analyses were possible.

First it was analysed how often longitudinal road markings are refurbished. The analysis was done based on the material and the location of the marking (left, middle and right line). From the responses given through the questionnaire, it was concluded that some countries do not have the data regarding the maintenance frequency. Overall, the results suggest that on motorways and primary roads in MS, painted road markings are usually renewed every year. In some cases, they are renewed every two years in the period 2-4 years after the application. Standard plastic markings (thermo and cold plastic) are usually renewed 2 to 4 years after the application. However, in some countries, mainly due to the weather and/or traffic conditions, standard plastic materials are renewed every year, while in some countries their service life is more than 4 years. Spray plastic materials are usually refurbished every year or in the period between 2 and 4 years.

Most of the countries (62%) estimated that they renew 26-50% of the road markings each year. Around one third of the countries which provided the answer estimated that they renew less than 25% of markings every year[20].

[20] Percentages are based on rough estimates provided by experts and may not present the actual situation correctly.

As seen from Figure 29, when deciding about the maintenance of road markings, most countries consider several factors, such as: type of the material, age of the marking, daytime and night-time visibility of the marking, AADT and the position of the marking.

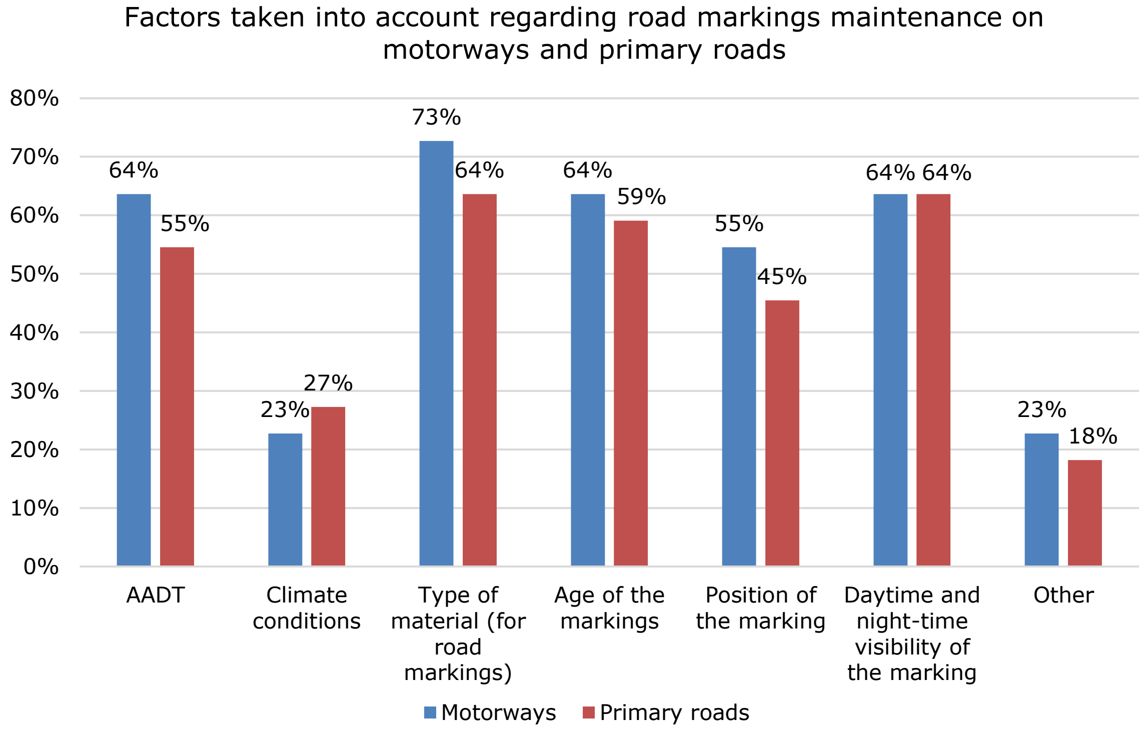


Figure 29. Representation of factors which affect the frequency of road markings maintenance on motorways and primary roads

Furthermore, most of the countries plan and decide about the renewal of road markings based on visual inspection as presented in Figure 30. However, in several Member States renewal plans are to some extent based on the daytime and night-time visibility measurements performed either using static or dynamic measuring method. In a few countries, the renewal is based on the annual plan regardless of the "true" state of the markings. Portugal has an interesting approach where measurements (daytime and night-time visibility) are conducted every two years and the decision about the renewal is based on these measurements. Furthermore, for primary roads, an algorithm is used to predict the service life of road markings and to decide when the renewal is needed. The algorithm takes into account several factors, such as: age of road markings, condition of the road surface, climate conditions, existence of sand and aggressive elements in the road environment and on the road surface.

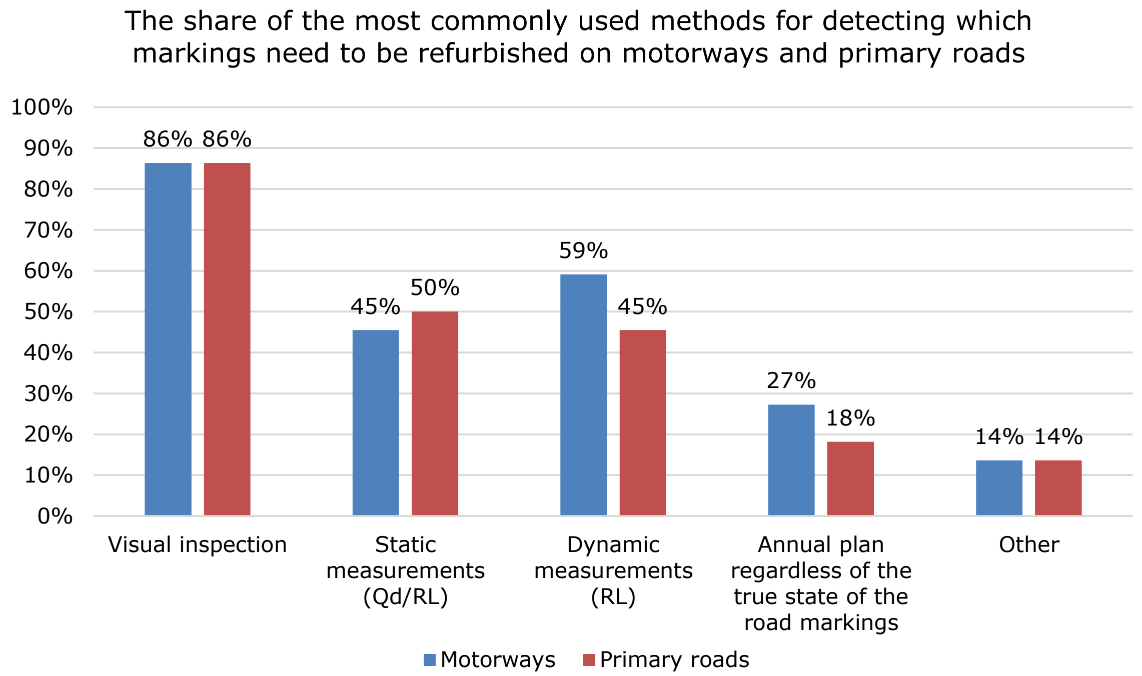


Figure 30. The share of the most commonly used methods for detecting which markings need to be refurbished on motorways and primary roads

Similar to road markings, the majority of the Member States (65%) replace their road signs if their quality is not sufficient or when they are damaged (39%). The quality is usually checked through visual inspection or retroreflectivity measurements. A few countries base the replacement of the signs on the annual plan regardless of their "true" state. The most common bases for the replacement of road signs are shown in Figure 31.

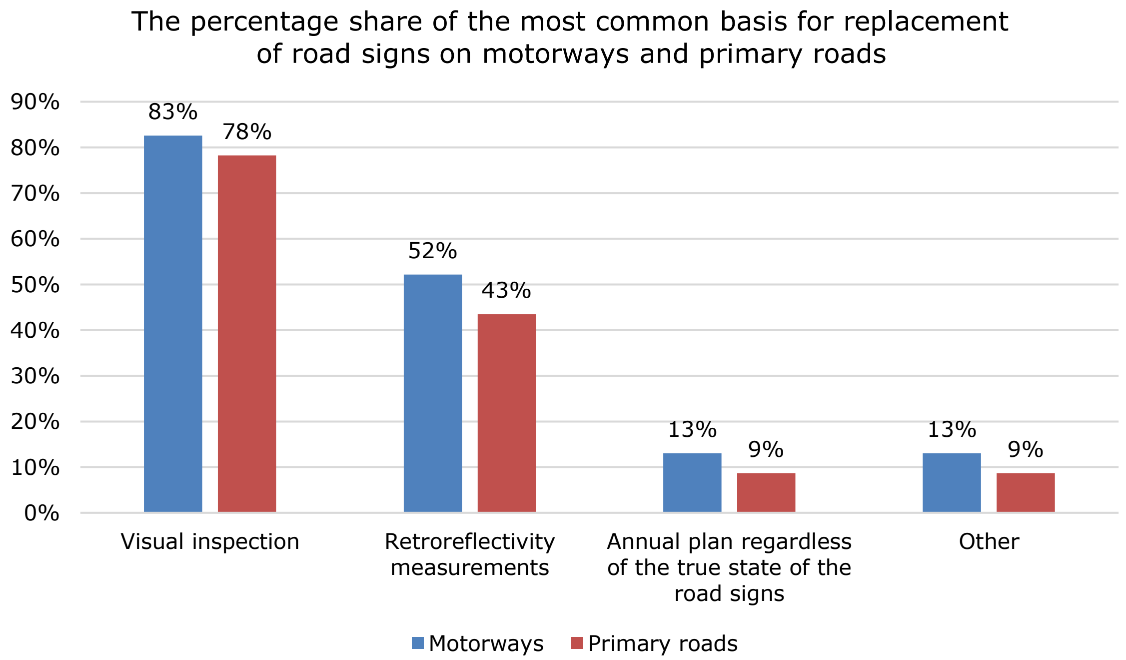


Figure 31. The share of the most commonly used methods for detecting which road signs should be replaced

Typically, road signs in Member States are replaced after ten years or later, as seen in Figure 32. In other words, countries mostly replace road signs after the expiry of the warranty period regardless of the class of the retroreflective sheeting. Experts estimated that on average around 10% of road signs are replaced every year.

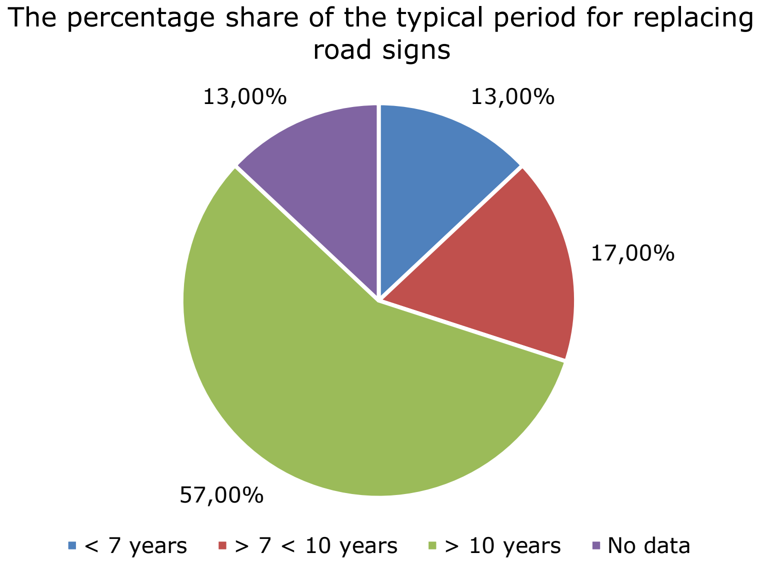


Figure 32. The percentage share of the typical period for replacing road signs

Most of the countries consider several factors when deciding which road signs need to be replaced. General visibility, along with the age of road signs and retroreflectivity measurement are mostly used factors for indicating timely replacement (Figure 33).

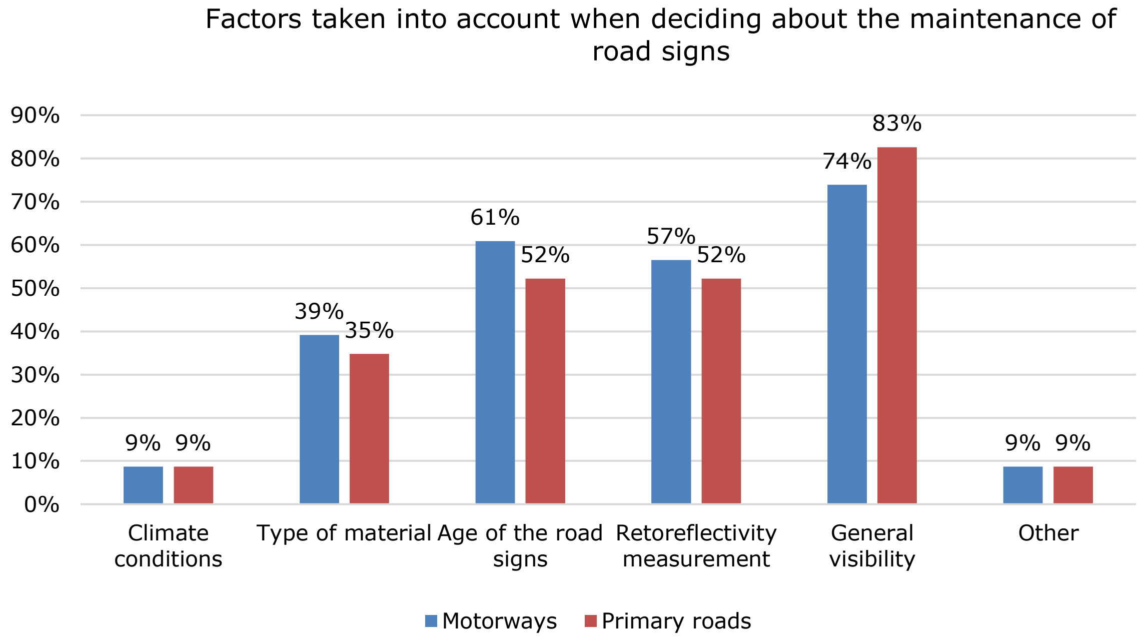


Figure 33. The percentage share of factors that are considered when deciding about the maintenance of road signs

To conclude this section about the maintenance practices for road markings and road signs, experts were asked to provide information regarding the annual maintenance costs of road markings and road signs in their country. Although in most of the countries, the provided information is based on estimations, it may be concluded that the annual cost of road markings maintenance is on average 4.784.077 EUR for motorways and 10.486.007 EUR for primary roads. On the other hand, average costs of road signs maintenance on motorways is 2.565.667 EUR and 8.134.976 EUR for primary roads as presented in Table 14.

Table 13. Average annual costs of the maintenance of road markings and road signs on motorways and primary roads

Type of road	The annual estimated costs of road markings maintenance *(EUR)*	The annual estimated costs of road signs maintenance *(EUR)*
Motorways	4.784.077 (Min = 100.000; Max = 18.000.000)	2.565.667 (Min = 10.000; Max = 10.000.000)
Primary roads	10.486.007 (Min = 300.000; Max = 32.000.000)	8.134.976 (Min = 30.000; Max = 30.000.000)

5. OVERVIEW OF PRACTICES, PROCEDURES AND METHODOLOGIES USED BY ROAD AUTHORITIES OUTSIDE THE MS

This section analyses common practices, procedures and methodologies used by road authorities outside the EU. The relevant data was collected based on a review of the professional literature and through consultations with different active stakeholders in the field.

5.1. Australian and New Zealand experience

a) Road markings

Recently, an extensive two-year project (2016-2018) was conducted in Australia and New Zealand to harmonise road markings [173]. The project was undertaken in collaboration with different stakeholders (Roads Australia, Roadmarking Industry Association of Australia) with the following objectives:

- achieve, where practicable, national harmonisation of road markings through the development of standardised test methods and specifications
- assess the impacts on relevant Austroads Guides, and
- provide input to the development of an Australian standard.

During the first part of the project, a review of current practices with respect to longitudinal markings and their performance specifications was conducted, based on which "good" practices were highlighted, and harmonisation specifications were proposed. The second part of the project resulted in agreed standards, specifications and maintenance recommendations for all road marking types.

Based on the aforementioned analysis as well as interviews and discussions with the relevant stakeholders, it was determined that most of the longitudinal markings in Australia are 100 mm and 150 mm wide. Most of the dashed longitudinal markings were categorized into two general types: 9-metre dashed with 3-metre spacing and 3-metre dashed with 9-metre spacing.

In terms of retroreflectivity (night-time visibility), different levels are defined based on the markings age. For white longitudinal markings in dry conditions, retroreflectivity should be as follows:

- 350 mcd/lx/m^2 or greater, within the first 30 days after opening to traffic
- 200 mcd/lx/m^2 or greater, at between 365 and 395 days after opening to traffic
- 150 mcd/lx/m^2 before remarking is required. This is the intervention level, i.e., the level at which road markings should be renewed
- 100 mcd/lx/m^2, overall minimal level

For yellow markings in dry conditions, retroreflectivity levels are as follows:

- 200 mcd/lx/m^2 or greater, within the first 30 days after opening to traffic
- 150 mcd/lx/m^2 or greater, at between 365 and 395 days after opening to traffic

- 100 mcd/lx/m², before renewal is required (intervention level)

The minimum wet retroreflectivity is set at 80 mcd/lx/m^2 for asphalt road surfaces and 100 mcd/lx/m^2 is recommended for concrete road surfaces. The luminance factor of markings must exceed 80 % for white markings and be in the range of 45–50% for yellow markings. On the concrete or light-coloured aggregate spray seal road surfaces, due to potential reduction in contrast, it is recommended to use contrast markings (black or coloured) to enhance visibility.

In addition, the study concluded that there is a need to include requirements for automated vehicles, which were mainly aimed at wider width (15 cm) and higher retroreflectivity (min 150 mcd/lx/m^2). The majority of road agencies have agreed to adopt the standard, recognising that further work may be necessary in terms of requirements for autonomous vehicles.

For this reason, a study which evaluated how machine-vision technologies interact with road infrastructure was conducted in 2020 by Austroads [145]. Based on the analysis of current infrastructure design and maintenance practices it was determined that they vary across the states. In general, the maintenance activities are usually based on a life treatment program, resurfacing and remarking, or an annual inspection based on night-time visibility. In states where annual inspection using retroreflectivity measurements is applied, the typical interventional level (i.e., renewal of markings) is set at 100 mcd/lx/m^2 (R_L). On the other hand, where a scheduled renewal program or combined method is in use, different schemes exist based on the generally acknowledged service life of different road marking materials. For example, paints are renewed every 6 – 12 months, plastic materials (cold and thermoplastic) every four years, while manufactured tapes are renewed in a 10-year cycle. Although significant effort has been made, the study highlighted that Australia still does not have an entirely uniform standard for road markings and, therefore, road authorities, to some extent, use a combination of national and state agency standards.

Furthermore, based on the literature review, current standards and practices as well as on-road and off-road tests conducted in the latest Austroads study [145] provided some valuable findings listed below[21]:

- The day-time contrast ratio between longitudinal road markings and the surrounding substrate should be at least 3-to-1.
- The contrast ratio for night-time visibility between longitudinal road markings and the surrounding substrate should be between 10-to-1 for asphalt road surfaces and 5-to-1 for concrete road surfaces.
- Overall, the minimal level of road markings night-time visibility should be 100 mcd/lx/m^2.
- In general, line detection performance deteriorates as night-time visibility reduces.

[21] A more detailed description of the study methodology is provided in Chapter 3.3.1.

- Road surface "brightness" can degrade machine-vision systems' ability to detect longitudinal road markings in some conditions because it reduces the contrast between the road marking and the substrate.
- Day-time visual clutter generally makes day-time lane detection less effective than at night.
- Rain reduces detectability of road markings by 32%
- Wet weather has different impacts on different machine-vision-enabled, lane-guidance functions. With minimal ambient lighting, the contrast ratio can be improved due to reduced specular diffusion. However, with excessive ambient lighting, the machine-vision systems can suffer from a "light bloom" effect reducing line detection.
- The suitable width of markings should be 150 mm for edge lines and 100 mm for dashed lines.
- Dashed lines are more likely than solid lines to be problematic for machine-vision lane detection.
- Using clear continuity lines on both sides of the lane, with no extended gaps and consistent lane width, is conducive to good lane detection.
- While many difficult-to-control factors can degrade the machine vision system's ability to detect longitudinal road markings, improving maintenance standards and design principles can generate significant network-wide gains.
- A cost-benefit analysis found that when longitudinal road markings are improved, the potential discounted crash benefits exceed the discounted capital and maintenance costs by a 3.28 benefits-to-costs ratio.

b) Road signs

Road signs in Australia and New Zealand are standardised through national regulations and standards. In Australia sign classification, basic sizes and shapes as well as design and other manufacturing specifications are defined through the Australian Road Rules and Australian Standards [174, 175]. On the other hand, in New Zealand signs are regulated through Land Transport Rule - Traffic Control Devices [176].

Although signs in both countries are standardised, they are regulated and enforced by each state's government through their respective road authorities. According to the study conducted by Austroads [171], there are different jurisdictional extensions in how each of the states and territories design and implement road signage. In other words, even though the aforementioned standards serve as a base for road signage, they do not capture the range of signs currently in place.

Therefore, further efforts are on-going and in 2020, Austroads published a *Guide to Traffic Management Part 10* with the aim of achieving consistency and uniformity of practice in respect of traffic control devices [177]. The guidelines complement Australian and New Zealand's standards by providing best practice beyond minimum standards within the guidelines, or providing guidance where standards are not appropriate or have not been developed. They cover various control devices including road signs.

Since both Australia and New Zealand have their own standards for road signs which are different from other countries which apply either the Vienna Convention or the USMUTCD, the details regarding the designs, placement or technical specifications will not be here addressed. However, the focus here will be on the Australia and New Zealand's experience regarding the readability and detectability of road signs by machine vision.

A comprehensive study with the aim of identifying the root causes of issues related to the proper and accurate functioning of TSR technology was conducted in 2018 [171]. The objectives of the study were to identify the issues related to current road sign deployments, to define recommendations for changes to road sign guidelines and standards and to develop a program of information and engagement with road authorities.

The study highlighted several recommendations for changes to enhance road sign readability across sign face design, installation and maintenance, sign positioning and location, electronic signs, vehicle mounted signs, and other advisory and information signs. Key findings identified in the study are as follows:

- The approach defined in the Vienna Convention for Road Signs is likely to be beneficial for TSR systems which preference shape and colour over text and a number of signs in Australia and New Zealand may be accurately read by TSR due to the text qualifications (END, AHEAD etc.) or conditional symbols

- Variation from installation and maintenance standards are a major issue. TSR systems perform well when dealing with standard speed signs, but machine-vision systems cannot handle significant variations to a core standard, at least at this stage. Also, TSR relies on signs being correctly located and maintained so that visible light and colour can be captured by the camera.

- The placement of signs near motorways, such as on side roads or off-ramps, is also a key issue. Signs visible from the main carriageway are often recognised by systems where they are not intended to apply. Signs located at roadwork sites were also problematic. Finally, collocation of signs, such as static signs applied next to, or near, electronic signs caused inconsistent readings by TSR.

- Since the TSR is calibrated to recognise shapes first and other features (text or colour) as secondary, the design of the sign influenced significantly the accuracy of the TSR. Speed advisory signs which use an annulus were often confused with statutory speed signs, and further qualifications such as school zone/activity zone timing, vehicle application, or application to cross roads were ignored. Furthermore, advisory/information signage or control signs currently cannot be read by TSR.

- Electronic signs could not be consistently read by TSR systems. The main problem is related to the refresh rate of signs and variability of pixel illumination which can vary between brands and designs. Other factors could include the sign size, height and approach angle, and the sign's power source.

- Both road authorities and OEMs interviewed agreed that there was significant divergence from national standards for road signs, which has led to inconsistencies across jurisdictions, and even within jurisdictions.
- Proper maintenance is essential if road signs are to remain effective and command the attention and respect of human drivers as well as TSR systems for the full warranted life of the sign. Thus, timely inspections and routine maintenance of signs is necessary. Maintenance practice should be in accordance with the local situation where road signs are placed.
- Well maintained databases of road signs are important since spatial databases are used as a supplement for TSR systems.
- There is a need for tighter cooperation between road authorities and OEMs in order to work through issues including electronic signs, development of new signs, and further development of TSR systems. Road authorities need better information from OEMs on requirements to inform changes to standards, or to plan changes to maintenance or programs.
- OEMs should be more collaborative in order to provide relevant working groups and road authorities with the information regarding problematic areas prior to system deployment.
- A special working group (Austroads Traffic Managers Working Group - TMWG) should govern road sing standards in order to support greater consistency, and to support road authorities. The work of the group should particularly focus on the identification of problematic signs for TSR systems, development of an electronic sign test method for readability by TSR systems as well as on the minimisation of the use of time, weather and traffic dependent changes in statutory speed limit signs and support the use of electronic VSLS.

5.2. Practices in the United States

In the United States, road markings and road signs are managed by the *Manual on Uniform Traffic Control Devices (MUTCD)* [178]. The first edition of MUTCD was approved as an American Standard in the 1935 with the aim of setting the minimum standards for all Traffic Control Devices (road signs, highway markings, electronic traffic signals, railroad crossings, and road-way construction zone areas) used on US roads and highways. Until today, several editions were published with the latest in 2009. The manual consists of nine parts each devoted to a special topic as follows: Part 1 – General, Part 2 – Signs (divided into seven subsections), Part 3 – Markings, Part 4 – Highway Traffic Signals, Part 5 -Traffic Control Devices for Low-Volume Roads, Part 6 - Temporary Traffic Control, Part 7 – Traffic Control for School Areas, Part 8 – Traffic Control for Railroad and Light Rail Transit Grade Crossings and Part 9 – Traffic Control For Bicycle Facilities.

In 2020 the Federal Highway Administration (FHWA) published national policy recommendations for road infrastructure agencies to consider as they plan for AVs. The proposed updates to the manual reflect state-of-the-art traffic research to help transportation agencies prepare for automated vehicles and other cutting-edge technologies. The proposal introduced several major changes in Part 2 and 3 (Signs and Markings) as well as a completely new part entitled “Automated Vehicles”.

a) Road markings

According to the MUTCD manual, the colour of road markings can be white, yellow, red, blue or purple. Black can be additionally used to improve visibility by providing adequate contrast. In general, a double line signifies a particular restriction, while a single solid line implies crossing prohibition. A broken line denotes a permissive situation (i.e., the crossing is allowed), while a dotted line indicates a change of lane function further down the road. Concerning the width of longitudinal road markings, the MUTCD proposes different measures based on the line type. The width of a normal line varies from 4 to 6 inches (i.e., 10 to 15 cm), while wide lines have double the width of normal lines. However, in order to enhance the detectability and readability of longitudinal road markings, new updates to the MUTCD proposed the use of 6-inch-wide (15 cm) markings on freeways, expressways and ramps as well as for edge lines on roadways with speeds higher than 40 mph (approximately 65 km/h). Several US states, such as California, Michigan and Florida, are already widening markings on their roads to 6-inch to accommodate automated vehicle technologies.

Furthermore, several other proposals are defined in order to enable higher accuracy of detection and readability of markings by machine-vision systems. Generally, markings should be consistent, correctly designed, adequately uniformed and in an appropriate condition. Dotted extension of right edge line and chevron markings in neutral areas in the exit lanes (Figure 34) are proposed as mandatory in order to improve the continuity of markings for automated vehicles. Also, to better accommodate machine vision, channelising devices at work zones should be at least 8 inches wide with retroreflective material for reliable machine detection in all weather conditions. Markings entering the work zone and those placed through lane shifts should be made with highly visible and continuous materials, not intermittent buttons and reflectors. For passive and active grade crossings, placement of markings should be consistent along a corridor to promote uniformity and to improve the ability of machine-vision technology to recognize highway-rail grade crossings. Raised road markers should be used only as a supplement to the markings, rather than as a substitute for them. In addition, uniform contrast markings should be used on light-coloured road surfaces to create greater contrast and enhance their visibility. Broken lines should be at least 10 ft in length with a maximum gap of 30 ft. Finally, it is recommended to avoid the use of decorative elements in crosswalks.

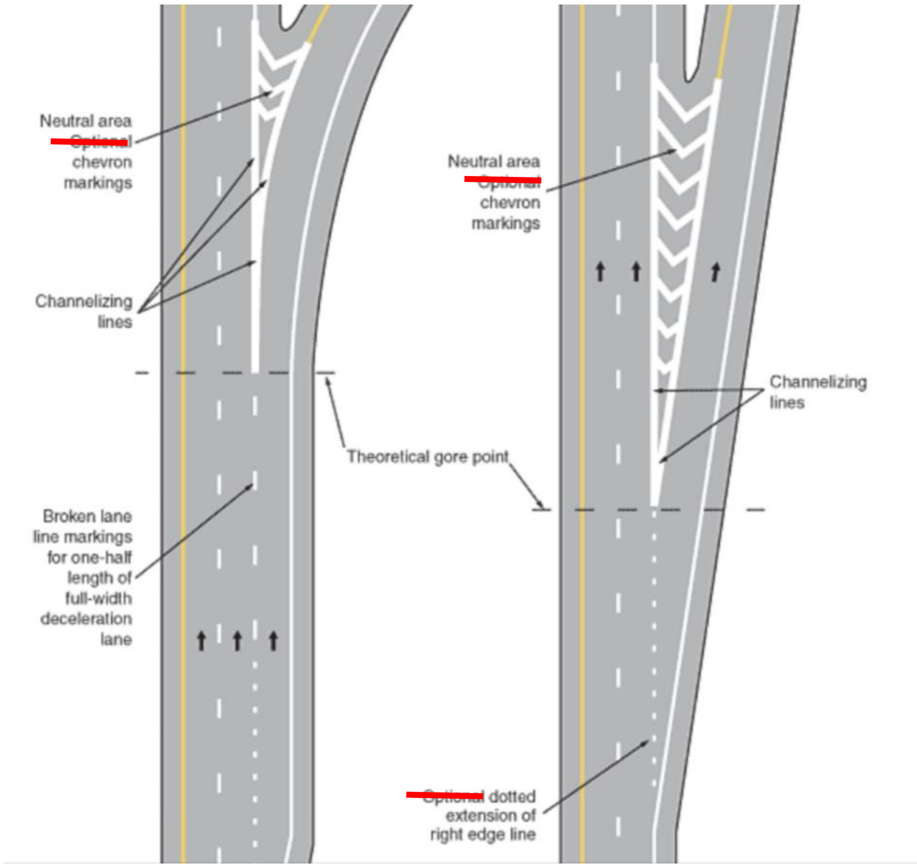


Figure 34. Example of MUTCD provisions intended to support ADAS/AV deployment (Source: [179])

From the visibility aspect, the MUTCD requires that road markings are visible at night and that they are retroreflective unless ambient illumination assures that they are adequately visible. Unlike road signs, the MUTCD manual has not yet provided guidance regarding the minimum levels of retroreflectivity of road markings. However, this was proposed in the supplemental notice of the proposed amendment (SNPA) in 2014 as a draft [180], while the official version was published in the Federal Register in 2017 [181]. The aforementioned amendments proposed that the minimum level of retroreflectivity is set at 50 mcd/lx/m2 for speed limits from 35 mph up to 70 mph (i.e., approximately 55 to 110 km/h). For high-speed roadways with speed limits over 70 mph, the minimum recommended retroreflectivity level is 100 mcd/lx/m2 [180, 181]. In addition to retroreflectivity, contrast is also considered crucial for road marking detectability for both human drivers and the ADAS system.

The proposal highlights that road authorities would be required to develop and implement a method for maintaining road marking retroreflectivity at minimum levels, but they would not be required to upgrade the markings by a specific date, nor to ensure that every marking is above the minimum retroreflectivity level at all times. Also, the proposed changes would allow flexibility in maintaining road marking retroreflectivity. Finally, a cost estimation of proposed upgrades was done. The analysis estimates that first year start-up implementation costs would be $29.4 million in order for all affected states and local road authorities to develop maintenance methods and purchase the necessary equipment. In addition, nationwide annual measurement and management activities of $14.9 million are expected to determine which markings require replacement. In the second and following years, if road authorities were to replace markings that do not meet the minimum retroreflectivity levels, despite the fact that there are no replacement compliance dates, there would be an estimated increase of approximately $52.5 million per year nationally from the current estimated road marking replacement expenditures. Therefore, it is highlighted that the proposed changes would not result in expenditure by state, local and tribal governments, in the aggregate, or by the private sector, of $100 million or more in any one year. Also, a Break-Even Benefit-Cost Estimation was done in order to calculate the number of fatalities that would need to be reduced annually to result in benefits equal to the calculated costs. The results of the aforementioned analysis indicated that the improvements of road markings would be cost-effective if they saved seven lives annually. Overall, FHWA "believes this is attainable and therefore, the potential benefits of the rule justify the costs" [180].

b) Road signs

The MUTCD manual contains standards, guidance and options for the signing of all types of highways and private roads open to public travel. This includes common specifications and the general appearance, colour and size of all signs. The basic requirements are defined based on the legibility of road signs legibility to help road users make appropriate and timely decisions. The attributes defined in the requirements include adequate visibility during the day and night and high legibility, meaning that the signs should be of appropriate size, colour and shape. Moreover, simplicity and uniformity of the design, size, colour, illumination and retroreflectivity are essential requirements for road signs regardless of the state in which they are used.

In general, the function of road signs defined in the manual is to provide regulations, warnings and guidance information for road users by means of words, symbols and arrows. The signs are divided into: 1) regulatory signs, barricades and gates; 2) warning signs and object markers; 3) guide signs for conventional roads; 4) guide signs for freeways and expressways; 5) toll road signs; 6) preferential and managed lane signs; 7) general information signs; 8) general service signs; 9) specific service (logo) signs; 10) tourist-oriented directional signs; 11) changeable message signs; 12) recreational and cultural interest area signs; and 13) emergency management signs.

According to the manual, road signs need to be designed, placed and maintained in such a way that they are understandable in a timely manner to permit a proper response. Therefore, simplicity and uniformity in design (shape, colour, dimensions, legends, borders and illumination or retroreflectivity), position and application are highlighted as important attributes. Standardised colours and shapes are specified so that several classes of signs can be promptly recognized.

Currently, there are several types of materials and techniques which provide adequate illumination and retroreflectivity. These are crucial factors when it comes to the legibility of those signs, specifically during the night. Table 15 displays the minimum levels of reflectivity for signs based on the sign colour and the sheeting type (i.e., material). As can be seen from the table, not all sheeting types apply to all sign colours.

Table 14. Minimum Maintained Retroreflectivity Levels

Sign Color	Sheeting Type (ASTM D4956-04)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
White on Green	W*; G ≥ 7	W ≥ 120; G ≥ 15			Post-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			²
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 75; O ≥ 75			³
White on Red	W ≥ 35; R ≥ 7				⁴
Black on White	W ≥ 50				–

¹ The minimum maintained retroreflectivity levels shown in this table are in units of cd/lx/m² measured at an observation angle of 0.2° and an entrance angle of -4.0°.
² For text and fine symbol signs measuring at least 48 inches and for all sizes of bold symbol signs
³ For text and fine symbol signs measuring less than 48 inches
⁴ Minimum sign contrast ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)
* This sheeting type shall not be used for this color for this application.

Bold Symbol Signs

- W1-1,2 – Turn and Curve
- W1-3,4 – Reverse Turn and Curve
- W1-5 – Winding Road
- W1-6,7 – Large Arrow
- W1-8 – Chevron
- W1-10 – Intersection in Curve
- W1-11 – Hairpin Curve
- W1-15 – 270 Degree Loop
- W2-1 – Cross Road
- W2-2,3 – Side Road
- W2-4,5 – T and Y Intersection
- W2-6 – Circular Intersection
- W2-7,8 – Double Side Roads
- W3-1 – Stop Ahead
- W3-2 – Yield Ahead
- W3-3 – Signal Ahead
- W4-1 – Merge
- W4-2 – Lane Ends
- W4-3 – Added Lane
- W4-5 – Entering Roadway Merge
- W4-6 – Entering Roadway Added Lane
- W6-1,2 – Divided Highway Begins and Ends
- W6-3 – Two-Way Traffic
- W10-1,2,3,4,11,12 – Grade Crossing Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3,4,16-22 – Large Animals
- W11-5 – Farm Equipment
- W11-6 – Snowmobile Crossing
- W11-7 – Equestrian Crossing
- W11-8 – Fire Station
- W11-10 – Truck Crossing
- W12-1 – Double Arrow
- W16-5P,6P,7P – Pointing Arrow Plaques
- W20-7 – Flagger
- W21-1 – Worker

Fine Symbol Signs (symbol signs not listed as bold symbol signs)

Special Cases

- W3-1 – Stop Ahead: Red retroreflectivity ≥ 7
- W3-2 – Yield Ahead: Red retroreflectivity ≥ 7; White retroreflectivity ≥ 35
- W3-3 – Signal Ahead: Red retroreflectivity ≥ 7; Green retroreflectivity ≥ 7
- W3-5 – Speed Reduction: White retroreflectivity ≥ 50
- For non-diamond shaped signs, such as W14-3 (No Passing Zone), W4-4P (Cross Traffic Does Not Stop), or W13-1P,2,3,6,7 (Speed Advisory Plaques), use the largest sign dimension to determine the proper minimum retroreflectivity level.

Source: [178]

The manual also recommends the use of several methods for maintaining signs retroreflectivity. These methods are:

a. Visual night-time inspection - the retroreflectivity of an existing sign is assessed by a trained road sign inspector who conducts a visual inspection from a moving vehicle during night-time conditions. Signs that are visually identified by the inspector to have retroreflectivity below the minimum levels should be replaced.

b. Measuring sign retroreflectivity - sign retroreflectivity is measured using a retroreflectometer. Signs with retroreflectivity below the minimum levels should be replaced.

c. Expected sign life - when signs are installed, the installation date is labelled or recorded so that the age of a sign is known. The age of the sign is compared to the expected service life of the sign which is based on the experience of sign retroreflectivity degradation in a geographic area compared to the minimum levels. Signs older than the expected life should be replaced.

d. Blanket replacement - all signs in an area/corridor, or of a given type, should be replaced at specified intervals. This eliminates the need to assess retroreflectivity or track the life of individual signs. The replacement interval is based on the expected sign life, compared to the minimum levels, for the shortest-life material used on the affected signs.

e. Control signs - replacement of signs in the field is based on the application and study of a sample of control signs. Control signs might be a small sample located in a maintenance yard or a sample of signs in the field. Control signs are monitored to determine the end of their retroreflective life. All field signs represented by the control sample should be replaced before the retroreflectivity of the control sample reaches the minimum levels.

f. Other methods - other methods developed based on engineering studies can be used.

Similar to road markings, the new updates to the MUTCD propose a more consistent application, correct location, appropriate condition and adequate uniformity of road signs. Also, signs should be well spread to prevent detection problems. Hence, the amount of information at any specific location should be limited to minimise potential sign clutter and improve detectability. Finally, the illuminated part of electronic-display signs should have a minimum refresh rate of 200 Hz to increase detectability by machine-vision systems.

6. STRENGTHS AND LIMITATIONS OF THE PRACTICES, PROCEDURES AND METHODOLOGIES IN MEMBER STATES

Strengths and limitations (weaknesses) of used practices have been identified based on the study methodology which included literature review of the impact of road markings and road signs on human drivers and ADAS and on the analysis of current specifications and standards related to road markings and road signs. The results of the aforementioned analysis are presented in Table 16.

Table 15. Strengths and limitations (weaknesses) of currently used practices in MS

STRENGTHS	LIMITATIONS (WEAKNESSES)
• All countries base their road markings and road signs on the Vienna Convention on Road Signs and Signals • Countries regulate road markings and road signs through national regulations, guidelines, specifications or standards • Most countries use durable materials for road markings on motorways • Most countries mainly use materials for road signs which have enhanced retroreflectivity properties (Class II & Class III) • Most countries use at least 12 cm wide longitudinal markings • Countries have defined minimal values for different quality properties of road markings and road signs • Countries conduct quality controls of road markings and road signs	• The lack of accurate database of road markings and road signs • Some countries use 10 cm wide longitudinal markings which, according to literature findings, may not be suitable for human drivers and ADAS in all conditions • Configurations of broken (dashed) lines differ among most of the countries • Dimensions of road signs both on motorways and primary roads differ among most of the countries • Some countries did not define the minimal quality levels for renewal of road markings • The majority of the countries did not define the minimal levels of night-time visibility in rainy conditions • Some countries defined visibility levels for new road markings which, according to literature findings, may not be adequate for human drivers and ADAS in all conditions • Quality control of road markings and road signs is mainly based on visual inspection, and it is not mandatory • Maintenance practices for road markings and road signs differ among countries to some extent

Based on the strengths and limitations, several opportunities for establishing commons specifications for road markings and road signs have been identified. These opportunities are as follows:

1) Increase the use of durable materials with increased visibility in wet conditions
2) Implement common minimal levels for daytime visibility of road markings on motorways and primary roads
3) Implement common minimal levels for night-time visibility of road markings in dry conditions on motorways and primary roads
4) Implement common minimal levels for night-time visibility of road markings in wet and rainy conditions on motorways and primary roads
5) Implement common minimal width of road markings on motorways and primary roads
6) Improve continuity of road markings (for example at exit ramps or intersections)
7) Improve the contrast of markings on concrete road surfaces with contrast markings
8) Improve the removal of old markings (traces of markings on the road surface after renewal)
9) Improve continuity of longitudinal road markings at exit ramp or intersections
10) Improve uniformity (design) of road markings
11) Implement common configuration of dashed longitudinal road markings
12) Implement common minimal dimensions of warning, prohibitory and mandatory road signs on motorways and primary roads
13) Implement minimal class of retroreflective materials for road signs on motorways and primary roads (depending on the sign type)
14) Establish digital maps of road markings and road signs
15) Improve the maintenance of road markings and road signs

Although the aforementioned opportunities show gaps and differences in current practices and standards among MS regarding road markings and road signs, there are certain threats at this stage to the establishment of common specifications. These threats are mainly related to:

1) Potential costs of the implementation of common specifications
2) Unwillingness to change the practices and standards which are currently in place
3) Potential higher costs of maintenance activities

4) Gaps in the scientific literature and uncertainty (to some extent) regarding the minimal needs for human drivers and ADAS

5) Unclear cost-benefit value of implementation of common specifications

6) Unclear “added value” to Member States of the implementation of common specifications

7. CONCLUSION

Road markings and road signs represent important elements of the road infrastructure that provide relevant information about current and upcoming situation on the road and thus help drivers to safely move through the road network. Although both the private sector and the national authorities in each Member State are pushing towards improving the overall quality of road markings and road signs, further efforts are needed. Current standards regarding road markings and road signs are based on human needs and to some extent may not be sufficient for the automated driver assistance systems (ADAS). Thus, a broader approach focusing on the needs and requirements of both human drivers and advanced vehicle systems is needed.

Therefore, the main aim of this study is to collect existing legislation, technical specifications and standards related to road markings and road signs among MS and to identify possible opportunities in order to establish common specifications. Those specifications would include different elements aimed at ensuring the operational use of road markings and road signs and to foster their effective readability and detectability for human drivers and automated driver assistance systems. When the establishment of common specifications is agreed, the Commission may adopt an implementing act to ensure their operational use in all Member States.

Therefore, this report provides the necessary information related to the: 1) impact of road markings and road sign on human drivers; 2) impact of road markings and road signs on machine vision; 3) minimal quality performance of road markings and road signs needed for both human drivers and ADAS in different conditions; 4) current practices, standards and specifications related to road markings and road signs in MS; and 5) practices related to road markings and road signs outside the EU.

The analysis of current practices led us to conclude that road markings and road signs in MS are regulated through national regulations, guidelines, specifications or standards. However, their performance level, i.e. quality characteristics as well as dimension and design differ among countries. Results of the comprehensive literature analysis indicate that current standards for visibility of road markings, in some countries, may not be adequate for both human drivers and ADAS in all conditions.

Overall, several opportunities for establishment of common specifications were identified. In order to further evaluate the potential and validity of identified opportunities, a more detailed analysis including a cost-benefit evaluation will be conducted in the future work.

REFERENCES

[1] World Health Organization (2017). Road Traffic Injuries.

[2] European Commission (2020). Road Safety Key Figures.

[3] Danish Road Traffic Accident Investigation Board (2014). Why Do Road Traffic Accidents Happen?

[4] Elvik, R., Hove, A., Vaa, T. and Sørensen, M. (2009). The Handbook of Road Safety Measures (second). Emerald Group Publishing Limited.

[5] Faculty of Transport and Traffic Sciences (2020). Analysis of Critical Factors of Road Accidents. Report [In Croatian]

[6] Babic, D., Fiolic, M., Babic, D., & Gates, T. (2020). Road Markings and Their Impact on Driver Behaviour and Road Safety: A Systematic Review of Current Findings. Journal of Advanced Transportation, Article ID 7843743. https://doi.org/10.1155/2020/7843743

[7] Jamson, S., & Mrozek, M. (2017). Is Three the Magic Number? The Role of Ergonomic Principles in Cross Country Comprehension of Road Traffic Signs. Ergonomics, 60(7), 1024–1031. https://doi.org/10.1080/00140139.2016.1245874

[8] Spielhofer, R., Osichenko, D., Leal, D., Benbow, E., & Wright, A. (2016a). Identifying the Key Characteristics for Road Marking and Stud Condition Measurements (Deliverable D1a and D2a; PREMiUM (Practical Road Equipment Measurement, Understanding and Management), p. 115). CEDR Call 2014: Asset Management and Maintenance.

[9] Spielhofer, R., Osichenko, D., Leal, D., Benbow, E., & Wright, A. (2016b). Identifying the Key Characteristics for Road Sign Condition Measurements (Deliverable D1b and D2b; PREMiUM (Practical Road Equipment Measurement, Understanding and Management), p. 105). CEDR Call 2014: Asset Management and Maintenance.

[10] 1.Elvik, R. (2010, May 25). Modern Technologies in Road Traffic Signs. 16th IRF world meeting, Lisbon, Portugal. http://www.crp.pt/docs/A28S38-66.pdf

[11] Babić, D., Ščukanec, A., & Babić, D. (2016). Determining the Correlation Between Daytime and Night-Time Road Markings Visibility. The Baltic Journal of Road and Bridge Engineering, 11(4), 283–290. https://doi.org/10.3846/bjrbe.2016.33

[12] ERF (2014). Marking the way towards a safer future: An ERF Position Paper on How Road Markings Can Make Our Road Safer. European Road Federation (ERF). http://erf.be/wp-content/uploads/2018/07/ERF-Paper-on-Road-Markings_release_v2.pdf

[13] Wegman, F., & Aarts, L. (2008). Advancing Sustainable Safety: National Road Safety Outlook for The Netherlands for 2005–2020 (p. 215). SWOV Institute for Road Safety Research.

[14] Dudek, C. L., Huchingson, R. D., & Woods, D. L. (1986). Evaluation of Temporary Pavement Marking Patterns in Work Zones: Proving Ground Studies. Transportation Research Record, 1086, 12–20. https://trid.trb.org/view.aspx?id=283796

[15] Dudek, C. L., Huchingson, R. D., & Creasey, F. T. (1987). Temporary Pavement Markings for Work Zones. Transportation Research Board National Research Council.

[16] Chang, K., Ramirez, M. V., Dyre, B., Mohamed, M., & Abdel-Rahim, A. (2019). Effects of Longitudinal Pavement Edgeline Condition on Driver Lane Deviation. Accident Analysis & Prevention, 128, 87–93. https://doi.org/10.1016/j.aap.2019.03.011

[17] Davidse, R., van Driel, C., & Goldenbeld, C. (2004). The Effect of Altered Road Markings on Speed and Lateral Position. SWOV Institute for Road Safety Research.

[18] Lundkvist, S. O., Ytterbom, U., & Runersjoe, L. (1990). Continuous Edgeline on Nine-Meter-Wide Two-Lane Roads (p. 23). Swedish Road and Traffic Research Institute.

[19] European Commission. (1999). European Cooperation in the Field of Scientific and Technical Research COST 331 Requirements for Horizontal Road Marking Final Report of the Action. Office for Official Publications of the European Communities.

[20] EuroRAP. (2013). Roads that Cars Can Read: A Quality Standard for Road Markings and Traffic Signs on Major Rural Roads. European Road Assessment Programme (EuroRAP). https://www.eurorap.org/wp-content/uploads/2015/03/roads_that_cars_can_read_2_spread1.pdf

[21] Calvo-Poyo, F., de Oña, J., Garach Morcillo, L., & Navarro-Moreno, J. (2020). Influence of Wider Longitudinal Road Markings on Vehicle Speeds in Two-Lane Rural Highways. Sustainability, 12(20), 8305. https://doi.org/10.3390/su12208305

[22] Gates, T. J., & Hawkins, H. G. (2002). The Use of Wider Longitudinal Pavement Markings (Research Report 0024-1). Texas Transportation Institute: College Station.

[23] Park, E. S., Carlson, P. J., Porter, R. J., & Andersen, C. K. (2012). Safety Effects of Wider Edge Lines on Rural, Two-Lane Highways. Accident Analysis & Prevention, 48, 317–325. https://doi.org/10.1016/j.aap.2012.01.028

[24] Carlson, P. J., Park, E. S., & Andersen, C. K. (2009). Benefits of Pavement Markings: A Renewed Perspective Based on Recent and Ongoing Research. Transportation Research Record, 2107(1), 59–68. https://doi.org/10.3141/2107-06

[25] Maroney, S., & Dewar, R. (1987). Alternatives to Enforcement in Modifying the Speeding Behavior of Drivers. Transportation Research Record, 1111, 121–125.

[26] Godley, S., Fildes, B., Triggs, T., & Brown, L. (1999). Perceptual Countermeasures: Experimentel Research (Road Safety Research Report No. CR182; p. 84). Monash University Accident Research Centre. https://trid.trb.org/view/651842

[27] Ariën, C. et al. (2017). The effect of Pavement Markings on Driving Behaviour in Curves: A Simulator Study. Ergonomics, 60(5), 701–713. https://doi.org/10.1080/00140139.2016.1200749

[28] Montella, A., Aria, M., D'Ambrosio, A., Galante, F., Mauriello, F., & Pernetti, M. (2011). Simulator Evaluation of Drivers' Speed, Deceleration and Lateral Position at Rural Intersections in Relation to Different Perceptual Cues. Accident Analysis & Prevention, 43(6), 2072–2084. https://doi.org/10.1016/j.aap.2011.05.030

[29] Montella, A., Galante, F., Mauriello, F., & Pariota, L. (2015). Effects of Traffic Control Devices on Rural Curve Driving Behavior. Transportation Research Record, 2492(1), 10–22. https://doi.org/10.3141/2492-02

[30] Hussain, Q., Pirdavani, A., Ariën, C., Brijs, T., & Alhajyaseen, W. (2018). The Impact of Perceptual Countermeasures on Driving Behavior in Rural-Urban Transition Road Segments: A Driving Simulator Study. Advances in Transportation Studies, 46, 83–96.

[31] Campbell, J. L. (Ed.). (2012). Human Factors Guidelines for Road Systems (2nd ed). Transportation Research Board.

[32] Finley, M. D., Carlson, P. J., Trout, N. D., & Jasek, D. L. (2002). Sign and Pavement Marking Visibility from The Perspective of Commercial Vehicle Drivers. Report FHWA/TX-03/4269-1, Texas Transportation Institute. https://trid.trb.org/view/660877

[33] Aktan, F., & Schnell, T. (2004). Performance Evaluation of Pavement Markings Under Dry, Wet, and Rainy Conditions in the Field. Transportation Research Record, 1877(1), 38–49. https://doi.org/10.3141/1877-05

[34] Commission Internationale de l'Eclairage. (1999). Requirements for Horizontal Road Marking (COST 331). Office for Official Publications of the European Communities. ftp://ftp.cordis.europa.eu/pub/cost-transport/docs/331-en.pdf.

[35] Rumar, K., & Marsh, D. K. (1998). Lane Markings in Night Driving: A Review of Past Research and of Present Situation (UMTRI-98-50). University of Michigan Transportation Research Institute.

[36] Sauter, G. (2015). Recommendation Handbook RAINVISION (Deliverable 2.1 of the Rainvision project). European Road Federation.

[37] Gibbons, R. B., Williams, B., & Cottrell, B. (2012). Refinement of Drivers' Visibility Needs during Wet Night Conditions. Transportation Research Record, 2272(1), 113–120. https://doi.org/10.3141/2272-13

[38] Gibbons, R. B., & Hankey, J. (2007). Wet Night Visibility of Pavement Markings: Dynamic Experiment. Transportation Research Record, 2015(1), 73–80. https://doi.org/10.3141/2015-09

[39] Higgins, L., Miles, J. D., Carlson, P., Burns, D., Aktan, F., Zender, M., & Kaczmarczik, J. M. (2009). Nighttime Visibility of Prototype Work Zone Markings under Dry, Wet-Recovery, and Rain Conditions. Transportation Research Record, 2107(1), 69–75. https://doi.org/10.3141/2107-07

[40] Parker, N. A., & Meja, M. S. J. (2003). Evaluation of Performance of Permanent Pavement Markings. Transportation Research Record, 1824(1), 123–132. https://doi.org/10.3141/1824-14

[41] Zwahlen, H. T., Schnell, T., & Miescher, S. (1999). Recognition Distances of Different Pavement Arrow Designs During Daytime and Nighttime. Transportation Research Record, 1692(1), 119–128. https://doi.org/10.3141/1692-13

[42] Pike, A., & Johnson, K. (2020). Identifying Wet Retroreflectivity Levels for Pavement Markings. Local Road Research Board. Available from http://www.dot.state.mn.us/research/TS/2020/202009TS.pdf

[43] Carlson, P. J., Miles, J. D., Pike, A. M., & Park, E. S. (2007). Evaluation of Wet-Weather and Contrast Pavement Marking Applications: Final Report (FHWA Report 0-5008-2). Texas Transportation Institute. https://trid.trb.org/view/836903

[44] Benekohal, R. F., Resende, P., Shim, E., Michaels, R. M., & Weeks, B. (1992). Highway Operations Problems of Elderly Drivers in Illinois. Report FHWA-IL-023, Illinois Department of Transportation.

[45] Staplin, L., Lococo, K., & Sim, T. (1990). Traffic Control Design Elements for Accommodating Drivers with Diminished Capacity. Report FHWA-RD-90-055, Federal Highway Administration.

[4546 Staplin, L., Harkey, D., Lococo, K., & Tarawneh, M. (1997). Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians. Volume I: Final report FHWA-RD-96-132. Federal Highway Administration.

[47] Allen, R. W., O'Hanlon, J. F., & McRuer, D. T. (1977). Driver's Visibility Requirements for Roadway Delineation, Vol. I: Effects of Contrast and Configuration on Driver Performance and Behaviour. Report FHWA-RD-77-165, Federal Highway Administration.

[48] Blackwell, H. R., & Taylor, J. H. (1969). Survey of Laboratory Studies of Visual Detection [NATO seminar on detection, recognition, and identification of line-of-sight targets]. Den Haag.

[49] Staplin, L., Lococo, K., & Byington, S. (1998). Older Driver Highway Design Handbook. Report FHWA-RD-97-135, Federal Highway Administration.

[50] Sarasua, W. A., Davis, W. J., Robertson, J., & Johnson, J. A. (2013). A Methodology for Evaluating Centerline Markings in Temperate Climates. Journal of Transportation of the Institute of Transportation Engineers, 5(1), 17–30.

[51] Burns, D. M., Hedblom, T. P., & Miller, T. W. (2008). Modern Pavement Marking Systems: Relationship Between Optics and Nighttime Visibility. Transportation Research Record, 2056(1), 43–51. https://doi.org/10.3141/2056-06

[52] National Cooperative Highway Research Program. (2013). Predicting the Initial Retroreflectivity of Pavement Markings from Glass Bead Quality (p. 74). NCHRP.

[53] O'Brien, J. (1989). Embedment and Retroreflectivity of Drop-On Glass Spheres in Thermoplastic Markings. Transportation Research Record, 1230, 37–44.

[54] Zhang, G., Hummer, J. E., & Rasdorf, W. (2010). Impact of Bead Density on Paint Pavement Marking Retroreflectivity. Journal of Transportation Engineering, 136(8), 773–781. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000142

[55] Craig, W. N., Sitzabee, W. E., Rasdorf, W. J., & Hummer, J. E. (2007). Statistical Validation of the Effect of Lateral Line Location on Pavement Marking Retroreflectivity Degradation. Public Works Management & Policy, 12(2), 431–450. https://doi.org/10.1177/1087724X07308773

[56] Zhang, G., Hummer, J. E., Rasdorf, W., & Mastin, N. (2013). The Impact of Pavement Type and Roughness on Paint Marking Retroreflectivity. Public Works Management & Policy, 18(1), 41–55. https://doi.org/10.1177/1087724X12438266

[57] Federal Highway Administration (1981). Highway Safety Stewardship Report (No. 107), Department of Transportation.

[58] Tsyganov, A. R., Machemehl, R., Warrenchuk, N. M., & Wang, Y. (2006). Before-After Comparison of Edgeline Effects on Rural Two-Lane Highways (p. 105). Texas Department of Transportation.

[59] National Cooperative Highway Research Program. (2002). Longterm Pavement Marking Practices Chapter Four: Traffic Crashes and Pavement Marking. NCHRP.

[60] Bahar, J. M., Masliah, M., Erwin, T., Tan, E., & Hauer, E. (2006). Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time. The National Academies Pres. https://doi.org/10.17226/23255.

[61] Dravitzki, V. K., Lester, T., & Wilkie, S. M. (2006). The Safety Benefits of Brighter Road Markings. Report, Land Transport, Wellington, New Zealand.

[62] Bektas, B. A., Gkritza, K., & Smadi, O. (2016). Pavement Marking Retroreflectivity and Crash Frequency: Segmentation, Line Type, and Imputation Effects. Journal of Transportation Engineering, 142(8). https://doi.org/10.1061/(ASCE)TE.1943-5436.0000863

[63] Carlson, P. J., Park, E. S., & Kang, D. H. (2013). Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety. Transportation Research Record, 2337(1), 59–66. https://doi.org/10.3141/2337-08

[64] Smadi, O., Souleyrette, R. R., Ormand, D. J., & Hawkins, N. (2008). Pavement Marking Retroreflectivity: Analysis of Safety Effectiveness. Transportation Research Record, 2056(1), 17–24. https://doi.org/10.3141/2056-03

[65] Smadi, O., Hawkins, N., Nlenanya, I., & Aldemir-Bektas, B. (2010). Pavement Markings and Safety (IHRB Project TR-580). Iowa Highway Research Board, Iowa State University.

[66] Carlson, P. J., Park, E. S., & Kang, D. H. (2013). Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety. Transportation Research Record, 2337(1), 59–66. https://doi.org/10.3141/2337-08

[67] Lyon, C., Persaud, B., & Eccles, K. (2015). Safety Evaluation of Wet-Reflective Pavement Markings. U.S. Department of Transportation Federal Highway Administration. Available at: https://www.fhwa.dot.gov/publications/research/safety/15065/15065.pdf

[68] Park, E. S., Carlson, P. J., & Pike, A. (2019). Safety Effects of Wet-Weather Pavement Markings. Accident Analysis & Prevention, 133, 105271. https://doi.org/10.1016/j.aap.2019.105271

[69] Burghardt, T. E., & Pashkevich, (2020). Materials Selection for Structured Horizontal Road Markings: Financial and Environmental Case Studies. European Transport Research Review, 12(1), 11. https://doi.org/10.1186/s12544-020-0397-x

[70] Burghardt, T. E., Pashkevich, A., & Bartusiak, J. (2020). Field Evaluation of Road Marking Systems Used for Renewal of Structured Pavement Markings – Preliminary Findings. Proceedings of 8th Transport Research Arena. Transport Research Arena TRA2020, Helsinki, Finland.

[71] Burghardt, T. E. (2018). High durability – High Retroreflectivity Solution for a Structured Road Marking System. Proceedings of International Conference on Traffic and Transport Engineering, 1096–1102.

[72] Burghardt, T. E., Pashkevich, A., & Mosböck, H. (2019). Yellow Pedestrian Crossings: From Innovative Technology for Glass Beads to a New Retroreflectivity Regulation. Case Studies on Transport Policy, 7(4), 862–870. https://doi.org/10.1016/j.cstp.2019.07.007

[73] ERF. (2015). Improved Signage for Better Roads: An ERF Position Paper towards improving Traffic Signs in European Roads. European Road Federation (ERF). http://www.erf.be/wp-content/uploads/2018/01/ERF_Position_Paper_on_Vertical_Signage_Final_7.pdf

[74] Khalilikhah, M., & Heaslip, K. (2016). The Effects of Damage on Sign Visibility: An Assist in Traffic Sign Replacement. Journal of Traffic and Transportation Engineering (English Edition), 3. https://doi.org/10.1016/j.jtte.2016.03.009

[75] Shinar, D., & Vogelzang, M. (2013). Comprehension of Traffic Signs with Symbolic Versus Text Displays. Transportation Research Part F: Traffic Psychology and Behaviour, 18, 72–82. https://doi.org/10.1016/j.trf.2012.12.012

[76] UNECE. (1968). The Vienna Convention on Road Signs and Signals. UNECE. https://unece.org/fileadmin/DAM/trans/conventn/Conv_road_signs_2006v_EN.pdf

[77] Castro, C., & Horberry, T. (2004). The Human Factors of Transport Signs. CRC Press - Taylor & Francis Group.

[78] Gartner, N. H., Messer, C. J., & Rathi, A. (1992). Traffic Flow Theory. Tuner Fairbank Highway Research Centre.

[79] Obeidat, M. S., Rys, M. J., Rys, A., & Du, J. (2016). Evaluation of Overhead Guide Sign Sheeting Materials to Increase Visibility and Safety for Drivers. Applied Ergonomics, 56, 136–143. https://doi.org/10.1016/j.apergo.2016.03.016

[80] Mace, D. (1988). Sign Legibility and Conspicuity. Transportation Research Board Special Report, 218. https://trid.trb.org/view/302105

[81] Ye, F., Carlson, P. J., & Jackson, M. N. (2018). Use of High Intensity Reflective Sheeting In lieu of External Lighting of Overhead Roadway Signs. Transport, 33(2), 437-445-437–445. https://doi.org/10.3846/16484142.2016.1264469

[82] Mace, D., Finkle, M., & Pennak, S. (1997). Day-time Photometric Requirements for Pedestrian Signals. Transportation Research Record, 1605(1), 41–48. https://doi.org/10.3141/1605-06

[83] Eugene, R., Russel, M. R., Rys, A., & Keck, M. (1999). Characteristics and Needs for Overhead Guide Sign Illumination from Vehicular Headlamps (FHWA-RD-98-135). Dept of Civil Engineering, Kansas State University.

[84] Schnell, T., Aktan, F., & Li, C. (2004). Traffic Sign Luminance Requirements of Nighttime Drivers for Symbolic Signs. Transportation Research Record, 1862(1), 24–35. https://doi.org/10.3141/1862-04

[85] Schnell, T., Yekhshatyan, L., & Daiker, R. (2009). Effect of Luminance and Text Size on Information Acquisition Time from Traffic Signs. Transportation Research Record, 2122(1), 52–62. https://doi.org/10.3141/2122-07

[86] Zwahlen, H., & Xiong, S. (2000). Legibility of Text on Traffic Signs as a Function of Luminance and Size. Presented at 80th Annual Meeting of the Transportation Research Board.

[87] Gatscha, M., & Reichenauer, S. (2010, May 25). On-Road Test 'Traffic Sign Performance' Glass Bead vs. Microprismatic Technology. 16th IRF world meeting, Lisbon, Portugal.

[88] Gatscha, M., Schreder, G., & Reichenauer, S. (2010, May 25). Analysis of Eye Movement Characteristics for Different Performance Classes of Retro-Reflective Traffic Signs. 16th IRF world meeting, Lisbon, Portugal.

[89] 3M. (2018). Explained: ASTM Standards for Traffic Signs (US). https://www.3m.com/wps/portal/en_US/3M/road-safety-us/resources/road-transportation-safety-center-blog/full-story/~/astm-standards-for-traffic-signs/?storyid=5011bc7a-64cc-4b28-93cd-84aa9707d5dd

[90] Preston, H., Arkins, K. C., Lebens, M., & Jensen, M. (2014). Traffic Sign Life Expectancy. Final Report No. 2014–20, Minnesota Department of Transportation Office of Materials and Road Research.

[91] Yee, D. (1985). Survey of the Traffic Safety Needs and Problems of Drivers Age 55 and Over. In Needs and Problems of Older Drivers: Survey Results and Recommendations ((J. L. Malfetti, ed.)). AAA Foundation for Traffic Safety.

[92] Chrysler, S. T., Carlson, P. J., & Hawkins, H. G. (2002). Nighttime Legibility of Ground-Mounted Traffic Signs as a Function of Font, Color, and Retro-reflective Sheeting Type (FHWA/TX-03/1796-2, TTI: 0-1796). College Station: Texas Transportation Institute.

[93] Garvey, P. M., Thompson-Kuhn, B., & Pietrucha, M. T. (1996). Sign Visibility: Research and Traffic Safety Overview. United States Sign Council.

[94] Caracoglia, S. (2003). Quantitative Analysis on The Understanding of Road Signs Within the Critical Decisional Distance: Comparison of Retro-Reflective Sheetings. Faculty of Engineering, Trieste university.

[95] Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). The impact Of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data. US Department of Transportation, National Highway Traffic Safety Administration.

[96] Treat, J. R. et al. (1979). Tri-level Study of the Causes of Traffic Accidents: Final Report: Causal Factor Tabulations and Assessments (Vol. I) (DOT Publication DOT HS-805 085). Institute for Research in Public Safety, Indiana University.

[97] Dewar, R. E. (1988). Criteria for the Design and Evaluation of Traffic Sign Symbols. Transportation Research Record, 1160, 1–6.

[98] Treisman, A. M., & Gelade, G. (1980). A Feature-Integration Theory of Attention. Cognitive Psychology, 12(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

[99] Zhang, T., & Chan, A. (2013). Traffic Sign Comprehension: A Review of Influential Factors and Future Directions for Research. Proceedings of the International Multi Conference of Engineers and Computer Scientists, 2, 1–5.

[100] Kraft, W. H., Homburger, W. S., & Pline, J. L. (2009). Traffic Engineering Handbook (sixth). Institute of Transportation Engineers. https://trid.trb.org/view/896024

[101] Handcock, H. E., Rogers, W. A., Schroeder, D., & Fisk, A. D. (2004). Safety Symbol Comprehension: Effects of Symbol Type, Familiarity, and Age. Human Factors, 46(2), 183–195. https://doi.org/10.1518/hfes.46.2.183.37344

[102] Ben-Bassat, T., & Shinar, D. (2006). Ergonomic Guidelines for Traffic Sign Design Increase Sign Comprehension. Human Factors, 48(1), 182–195. https://doi.org/10.1518/001872006776412298

[103] Ben-Bassat, T., & Shinar, D. (2015). The Effect of Context and Drivers' Age on Highway Traffic Signs Comprehension. Transportation Research Part F: Traffic Psychology and Behaviour, 33, 117–127. https://doi.org/10.1016/j.trf.2015.07.009

[104] Ben-Bassat, T. (2019). Are Ergonomically Designed Road Signs More Easily Learned? Applied Ergonomics, 78, 137–147. https://doi.org/10.1016/j.apergo.2019.02.009

[105] Dewar, R. E., Kline, D. W., & Swanson, H. A. (1994). Age Differences in Comprehension of Traffic Sign Symbols. Transportation Research Record, 1456, 1–10.

[106] Edworthy, J., & Adams, A. (1996). Warning Design: A Research Prospective. Taylor and Francis.

[107] Ng, A. W. Y., & Chan, A. H. S. (2007). The Guessability of Traffic Signs: Effects of Prospective-User Factors and Sign Design Features. Accident Analysis & Prevention, 39(6), 1245–1257. https://doi.org/10.1016/j.aap.2007.03.018

[108] Ou, Y.-K., & Liu, Y.-C. (2012). Effects of Sign Design Features and Training on Comprehension of Traffic Signs in Taiwanese and Vietnamese User Groups. International Journal of Industrial Ergonomics, 42(1), 1–7. https://doi.org/10.1016/j.ergon.2011.08.009

[109] Shinar, D., Dewar, R. E., Summala, H., & Zakowska, L. (2003). Traffic Sign Symbol Comprehension: A Cross-Cultural Study. Ergonomics, 46(15), 1549–1565. https://doi.org/10.1080/0014013032000121615

[110] Al-Madani, H., & Al-Janahi, A. R. (2002). Role of Drivers' Personal Characteristics in Understanding Traffic Sign Symbols. Accident Analysis & Prevention, 34(2), 185–196. https://doi.org/10.1016/S0001-4575(01)00012-4

[111] Bañares, J. R., Caballes, S. A., Serdan, M. J., Liggayu, A. T., & Bongo, M. F. (2018). A Comprehension-Based Ergonomic Redesign of Philippine Road Warning Signs. International Journal of Industrial Ergonomics, 65, 17–25. https://doi.org/10.1016/j.ergon.2018.01.011

[112] Ben-Bassat, T. (2013). The Effect of Context and Ergonomic Design of Traffic Signs on Driver Comprehension – A Preliminary Evaluation. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 57(1), 1943–1947. https://doi.org/10.1177/1541931213571434

[113] Makinde, O. O., & Oluwasegunfunmi, V. (2014). Comprehension of Traffic Control Devices Amongst Urban Drivers–A Study of Ado-Ekiti, Ekiti State, Nigeria. Eur. J. Eng. Technol., 2(1), 9–19.

[114] Ben-Bassat, T., & Shinar, D. (2018). The Influence of Sign Variations on Drivers' Comprehension. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 62(1), 1918–1922. https://doi.org/10.1177/1541931218621435

[115] Borowsky, A., Shinar, D., & Parmet, Y. (2008). Sign location, Sign Recognition, and Driver Expectancies. Transportation Research Part F: Traffic Psychology and Behaviour, 11(6), 459–465. https://doi.org/10.1016/j.trf.2008.06.003

[116] Babić, D., Babić, D., & Scukanec, A. (2017). The Impact of Road Familiarity on the Perception of Traffic Signs – Eye Tracking Case Study. Environmental Engineering, 10th international conference, Vilnius, Lithuania. https://doi.org/10.3846/enviro.2017.131

[117] Lajunen, T., Hakkarainen, P., & Summala, H. (1996). The Ergonomics of Road Signs: Explicit and Embedded Speed Limits. Ergonomics, 39(8), 1069–1083. https://doi.org/10.1080/00140139608964528

[118] Chan, A. H. S., & Ng, A. W. Y. (2010). Investigation of Guessability of Industrial Safety Signs: Effects of Prospective-User Factors and Cognitive Sign Features. International Journal of Industrial Ergonomics, 40(6), 689–697. https://doi.org/10.1016/j.ergon.2010.05.002

[119] ECMT. (1996). Siting of Road Signs and Signals: First Steps Towards a Common Practice. [Unpublished survey data]. European Conference of Ministers of Transport, Group on Road Traffic Signs and Signals.

[120] Theeuwes, J., & Godthelp, H. (1995). Self-explaining Roads. Safety Science, 19(2), 217–225. https://doi.org/10.1016/0925-7535(94)00022-U

[121] Ferko, M., Stažnik, A., Modrić, M., & Dijanić, H. (2019). The Impact of Traffic Sign Quality on the Frequency of Traffic Accidents. Promet – Traffic & Transportation, 31(5), 549–558. https://doi.org/10.7307/ptt.v31i5.3023

[122] Šarić, Ž., Xu, X., Duan, L., & Babić, D. (2018). Identifying the Safety Factors Over Traffic Signs in State Roads Using a Panel Quantile Regression Approach. Traffic Injury Prevention, 19(6), 607–614. https://doi.org/10.1080/15389588.2018.1476688

[123] Xu, X., Šarić, Ž., Zhu, F., & Babić, D. (2018). Accident Severity Levels and Traffic Signs Interactions in State Roads: A Seemingly Unrelated Regression Model in Unbalanced Panel Data Approach. Accident; Analysis and Prevention, 120, 122–129. https://doi.org/10.1016/j.aap.2018.07.037

[124] Penmetsa, P., & Pulugurtha, S. S. (2018). Modeling Crash Injury Severity by Road Feature to Improve Safety. Traffic Injury Prevention, 19(1), 102–109. https://doi.org/10.1080/15389588.2017.1335396

[125] Filtness, A. J., Larue, G., Schramm, A., Fuller, J., Rakotonirainy, A., Han, C., & Cairney, P. (2017). Safety Implications of Co-Locating Road Signs: A Driving Simulator Investigation. Transportation Research Part F: Traffic Psychology and Behaviour, 47, 187–198. https://doi.org/10.1016/j.trf.2017.04.007

[126] Metz, B., & Krüger, H.-P. (2014). Do Supplementary Signs Distract the Driver? Transportation Research Part F: Traffic Psychology and Behaviour, 23, 1–14. https://doi.org/10.1016/j.trf.2013.12.012

[127] Polders, E. et al. (2015). ElderSafe: Risks and Countermeasures for Road Traffic of Elderly in Europe (N° MOVE/C4/2014-244). European Commission – Directorate-General for mobility and transport (DG-MOVE).

[128] Lu, M., Wevers, K. & van der Heijden, R. (2005). Technical Feasibility of Advanced Driver Assistance Systems (ADAS) For Road Traffic Safety. Transportation Planning and Technology, 28(3), 167–187. https://doi.org/10.1080/03081060500120282

[129] Jermakian, J. S. (2011). Crash Avoidance Potential of Four Passenger Vehicle Technologies. Accident Analysis & Prevention, 43(3), 732–740. https://doi.org/10.1016/j.aap.2010.10.020.

[130] Jermakian, J. S. (2012). Crash Avoidance Potential of Four Large Truck Technologies. Accident Analysis & Prevention, 49, 338–346. https://doi.org/10.1016/j.aap.2010.10.033.

[131] Kusano, K. D. & Gabler, H. C. (2015). Comparison of Expected Crash and Injury Reduction from Production Forward Collision and Lane Departure Warning Systems. Traffic Injury Prevention, 16(2), S109–S114. https://doi.org/10.1080/15389588.2015.1063619.

[132] Penmetsa, P., Hudnall, M. & Nambisan, S. (2019). Potential Safety Benefits of Lane Departure Prevention Technology. IATSS Research, 43(1):21–26. https://doi.org/10.1016/j.iatssr.2018.08.002.

[133] Tan, H., Zhao, F., Hao, H. & Liu, Z. (2020). Estimate of Safety Impact of Lane Keeping Assistant System on Fatalities and Injuries Reduction for China: Scenarios Through 2030. Traffic Injury Prevention, 21(2), 156-162. https://doi.org/10.1080/15389588.2020.1711518.

[134] AAA Foundation. (2018). Potential Reduction in Crashes, Injuries and Deaths from Large-Scale Deployment of Advanced Driver Assistance Systems. Available at: https://aaafoundation.org/potential-reduction-in-crashes-injuries-and-deaths-from-large-scale-deployment-of-advanced-driver-assistance-systems/ (accessed Mar. 16, 2021).

[135] Hickman, J. S. et al. (2015). Efficacy of Roll Stability Control and Lane Departure Warning Systems Using Carrier-Collected Data. Journal of Safety Research, 52, 59–63. https://doi.org/10.1016/j.jsr.2014.12.004.

[136] Sternlund, S. (2017). The Safety Potential of Lane Departure Warning Systems - A Descriptive Real-world Study of Fatal Lane Departure Passenger Car Crashes in Sweden. Traffic Injury Prevention, 18(1):18-23. https://doi.org/10.1080/15389588.2017.1313413.

[137] Spicer, R. et al. (2018). Field Effectiveness Evaluation of Advanced Driver Assistance Systems. Traffic Injury Prevention, 19(2), 91–95. https://doi.org/10.1080/15389588.2018.1527030.

[138] Cicchino, J. B. (2018). Effects of Lane Departure Warning on Police-reported Crash Rates. Journal of Safety Research, 66, 61-70. https://doi.org/10.1016/j.jsr.2018.05.006.

[139] TomTom. Intelligent Speed Assistance & Speed Sign Recognition. https://www.tomtom.com/use-cases/intelligent-speed-assistance/ (accessed Mar. 16, 2021).

[140] Lane Keeping Assist System (LKAS). Available at: http://techinfo.honda.com/rjanisis/pubs/QS/AH/BTY31919GW/enu/GUID-A94041EB-E74D-4902-BEF4-1CF4CA97EC55.html (accessed Apr. 30, 2021).

[141] Tang, J., Li, S. & Liu, P. (2021). A review of Lane Detection Methods Based on Deep Learning. Pattern Recognition, 111, 107623. https://doi.org/10.1016/j.patcog.2020.107623.

[142] Narote, S. P., Bhujbal, P. N., Narote, A. S. & Dhane, D. M. (2018). A Review of Recent Advances in Lane Detection and Departure Warning System. Pattern Recognition, 73, 216–234. https://doi.org/10.1016/j.patcog.2017.08.014.

[143] Forson, E. (2017). Teaching Cars to See — Advanced Lane Detection Using Computer Vision. Medium. https://towardsdatascience.com/teaching-cars-to-see-advanced-lane-detection-using-computer-vision-87a01de0424f (accessed Mar. 16, 2021).

[144] '20110629-Roads-That-Cars-Can-Read-June-2011.pdf'. Accessed: Mar. 17, 2021. [Online]. Available: http://www.eurorap.org/wp-content/uploads/2015/04/20110629-Roads-That-Cars-Can-Read-June-2011.pdf.

[145] Austroads (2020). Implications of Pavement Markings for Machine Vision. Report. Available: https://austroads.com.au/publications/connected-and-automated-vehicles/ap-r633-20.

[146] Nassu, B. T. & Ukai, M. (2010). Automatic Recognition of Railway Signs Using SIFT Features. In 2010 IEEE Intelligent Vehicles Symposium, 348–354. https://doi.org/10.1109/IVS.2010.5548127.

[147] Creusen, I. M., Wijnhoven, R. G. J., Herbschleb, E. & de With, P. H. N. (2010). Color Exploitation in Hog-Based Traffic Sign Detection. In 2010 IEEE International Conference on Image Processing, 2669–2672. https://doi.org/10.1109/ICIP.2010.5651637.

[148] Duan, J. & Viktor, M. (2015). Real Time Road Edges Detection and Road Signs Recognition. In 2015 International Conference on Control, Automation and Information Sciences (ICCAIS), 107–112. https://doi.org/10.1109/ICCAIS.2015.7338642.

[149] Kaarmukilan, S. P., Poddar, S. & Amal Thomas, K. (2020). FPGA Based Deep Learning Models for Object Detection and Recognition Comparison of Object Detection Comparison of object detection models using FPGA. In 2020 Fourth International Conference on Computing Methodologies and Communication (ICCMC), 471–474. https://doi.org/10.1109/ICCMC48092.2020.ICCMC-00088.

[150] Zhao, X. et al. (2020). Fusion of 3D LIDAR and Camera Data for Object Detection in Autonomous Vehicle Applications. IEEE Sensors Journal, 20(9), 4901–4913. https://doi.org/10.1109/JSEN.2020.2966034.

[151] Wahyono, Kurnianggoro, L. & Jo, K. (2015). Traffic Sign Recognition and Tracking for a Vision-based Autonomous Vehicle Using Optimally Selected Features. In 54th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE), 1419–1422. https://doi.org/10.1109/SICE.2015.7285415.

[152] Magnussen, A. F. et al. (2020). A Survey of the Inadequacies in Traffic Sign Recognition Systems for Autonomous Vehicles. International Journal of Performability Engineering, 16(10), 1588-1597. 10.23940/ijpe.20. https://doi.org/10.p10.15881597.

[153] ASIMOB (2021). Automated Monitoring for Traffic Signs. Presented at the EC EGRIS SG1 meeting on 15th April 2021.

[154] Hadi, M., Sinha, P. & Easterling IV, J. R. (2007). Effect of Environmental Conditions on Performance of Image Recognition–Based Lane Departure Warning System. Journal of the Transportation Research Board, 2000(1), 114-120. https://doi.org/10.3141/2000-14.

[155] Lundkvist, S. O. & Fors, C. (2010) Lane Departure Warning System – LDW, Linköping: VTI.

[156] European Union Road Federation (2013). Marking the Way Towards a Safer Future, Brussels: ERF.

[157] Potters Industry and Mobileye (2016). Pavement Markings Guiding Autonomous Vehicles - A Real World Study. Available at: https://higherlogicdownload.s3.amazonaws.com/AUVSI/14c12c18-fde1-4c1d-8548-035ad166c766/UploadedImages/documents/Breakouts/20-2%20Physical%20Infrastructure.pdf

[158] Carlson, P. J. & Poorsartep, M. (2017). Enhancing the Roadway Physical Infrastructure for Advanced Vehicle Technologies: A Case Study in Pavement Markings for Machine Vision and a Road Map Towards a Better Understanding. In the 96th Annual Meeting Transportation Research Board, Washington, USA.

[159] American Traffic Safety Services Association (2019). ATSSA Policy on Road Markings for Machine Vision Systems. Available at: https://www.reflective-

systems.com/wp-content/uploads/2019/04/Policy-re-Road-Markings-for-Machine-Vision-Systems.pdf.

[160] Visibility of Road Markings to Machine Vision – Climatic Wind Tunnel Experiment (2020). SWARCO, Gmbh.

[161] Pappalardo, G., Cafiso, S., Di Graziano, D. & Severino, A. (2021). Decision Tree Method to Analyze the Performance of Lane Support Systems. Sustainability, 13(2):846. https://doi.org/10.3390/su13020846

[162] Texas A&M Transportation Institute (2018). Evaluation of The Effects of Pavement Marking Characteristics on Detectability by ADAS Machine Vision. Report, NCHRP Project 20-102(6).

[163] Cao, J., Song, C., Peng, S., Xiao, F. & Song, S. (2019). Improved Traffic Sign Detection and Recognition Algorithm for Intelligent Vehicles. Sensors (Switzerland), 19(18). https://doi.org/10.3390/s19184021

[164] Dewi, C., Chen, R. C. & Yu, H. (2020). Weight Analysis for Various Prohibitory Sign Detection and Recognition Using Deep Learning. Multimedia Tools and Applications, 79(43–44), 32897–32915. https://doi.org/10.1007/s11042-020-09509-x

[165] Gil Jiménez, P., Bascón, S. M., Moreno, H. G., Arroyo, S. L. & Ferreras, F. L. (2008). Traffic Sign Shape Classification and Localization Based on the Normalized FFT of the Signature of Blobs and 2D Homographies. Signal Processing, 88(12), 2943–2955. https://doi.org/10.1016/j.sigpro.2008.06.019

[166] Tian, Y., Gelernter, J., Wang, X., Li, J. & Yu, Y. (2019). Traffic Sign Detection Using a Multi-Scale Recurrent Attention Network. IEEE Transactions on Intelligent Transportation Systems, 20(12), 4466–4475. https://doi.org/10.1109/TITS.2018.2886283

[167] Gudigar, A., Chokkadi, S. & Raghavendra, U. (2016). A Review on Automatic Detection and Recognition of Traffic Sign. Multimedia Tools and Applications, 75(1), 333–364. https://doi.org/10.1007/s11042-014-2293-7

[168] Liu, C., Li, S., Chang, F. & Wang, Y. (2019). Machine Vision Based Traffic Sign Detection Methods: Review, Analyses and Perspectives. IEEE Access, 7, 86578–86596. https://doi.org/10.1109/ACCESS.2019.2924947

[169] Wali, S. B. et al. (2019). Vision-based Traffic Sign Detection and Recognition Systems: Current Trends and Challenges. Sensors (Switzerland), 19(9). https://doi.org/10.3390/s19092093

[170] Zourlidou, S. & Sester, M. (2019). Traffic Regulator Detection and Identification from Crowdsourced Data - A Systematic Literature Review. ISPRS International Journal of Geo-Information, 8(11), 491. https://doi.org/10.3390/ijgi8110491

[171] Austroads. (2018). Implications of Traffic Sign Recognition (TSR) Systems for Road Operators, Technical report AP-R580-18.

[172] EN 1436:2018 - Road Marking Materials – Road Marking Performance for Road Users and Test Methods

[173] Austroads (2018). Harmonisation of Pavement Markings and National Pavement Marking Specification, Technical report AP-R578-18.

[174] Standards Australia (2014). AS 1742. Manual of Uniform Control Traffic Devices. Standards Australia.

[175] Standards Australia (2018). AS 1743. Road Signs - Specifications. Standards Australia.

[176] New Zealand Transport Agency (2010). Traffic Control Devices Manual.

[177] Austroads (2020). Guide to Traffic Management Part 10: Transport Control – Types of Devices

[178] Federal Highway Administration (2009). Manual on Uniform Traffic Control Devices (MUTCD).

[179] Carlson, P. Briefing MUTCD NPA, Virtual Meeting via Zoom (February 11, 2020)

[180] Federal Highway Administration (2014). Assessment of Economic Impacts of SNPA Proposed Minimum Levels of Pavement Marking Retroreflectivity. Report FHWA-SA-14-016. Available at: https://safety.fhwa.dot.gov/roadway_dept/night_visib/fhwasa14016.cfm

[181] Federal Highway Administration (2017). Supplemental Notice of Proposed Amendments - National Standards for Traffic Control Devices; the Manual on Uniform Traffic Control Devices for Streets and Highways; Maintaining Pavement Marking Retroreflectivity. Available online: https://www.regulations.gov/document/FHWA-2009-0139-0124

APPENDIX 1

Climate classes, according to the Köppen climate classification map, in MS analysed in this study

Country	Name	Class
Austria	Humid Continental Mild Summer, Wet All Year	Dfb
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Tundra Climate	ET
	Temperate Oceanic Climate	Cfb
Belgium	Temperate Oceanic Climate	Cfb
Bulgaria	Humid Subtropical Climate	Cfa
	Humid Continental Mild Summer, Wet All Year	Dfb
	Humid Continental Hot Summers with Year Around Precipitation	Dfa
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Ice Cap Climate	EF
	Tundra Climate	ET
	Humid Continental Climate - Dry Cool Summer	Dsb
Croatia	Humid Continental Mild Summer, Wet All Year	Dfb
	Temperate Oceanic Climate	Cfb
	Humid Subtropical Climate	Cfa
	Hot-Summer Mediterranean Climate	Csa
	Warm-Summer Mediterranean Climate	Csb
Cyprus	Hot-Summer Mediterranean Climate	Csa
	Hot Semi-Arid Climate	BSh
Estonia	Humid Continental Mild Summer, Wet All Year	Dfb
Finland	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Humid Continental Mild Summer, Wet All Year	Dfb
France	Temperate Oceanic Climate	Cfb
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Humid Continental Mild Summer, Wet All Year	Dfb
	Tundra Climate	ET
	Warm-Summer Mediterranean Climate	Csb
Germany	Humid Continental Mild Summer, Wet All Year	Dfb
	Temperate Oceanic Climate	Cfb
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Humid Subtropical Climate	Cfa
Hungary	Humid Continental Mild Summer, Wet All Year	Dfb
	Humid Continental Hot Summers with Year Around Precipitation	Dfa
Iceland	Tundra Climate	ET
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Continental Subarctic - Cold Dry Summer	Dsc
	Subpolar Oceanic Climate	Cfc
Italy	Hot-Summer Mediterranean Climate	Csa
	Humid Subtropical Climate	Cfa
	Warm-Summer Mediterranean Climate	Csb
	Cold Semi-Arid Climate	BSk
	Humid Continental Mild Summer, Wet All Year	Dfb

	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Temperate Oceanic Climate	Cfb
Latvia	Humid Continental Mild Summer, Wet All Year	Dfb
Lithuania	Humid Continental Mild Summer, Wet All Year	Dfb
Luxembourg	Temperate Oceanic Climate	Cfb
Norway	Subarctic with Cool Summers And Year Around Rainfall	Dfc
	Tundra Climate	ET
	Temperate Oceanic Climate	Cfb
	Subpolar Oceanic Climate	Cfc
	Continental Subarctic - Cold Dry Summer	Dsc
	Humid Continental Mild Summer, Wet All Year	Dfb
Poland	Humid Continental Mild Summer, Wet All Year	Dfb
Portugal	Hot-Summer Mediterranean Climate	Csa
	Warm-Summer Mediterranean Climate	Csb
Romania	Humid Continental Mild Summer, Wet All Year	Dfb
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Tundra Climate	ET
	Humid Continental Hot Summers with Year Around Precipitation	Dfa
	Temperate Oceanic Climate	Cfb
Slovakia	Humid Continental Mild Summer, Wet All Year	Dfb
	Tundra Climate	ET
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Humid Continental Hot Summers with Year Around Precipitation	Dfa
Slovenia	Temperate Oceanic Climate	Cfb
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Tundra Climate	ET
	Subpolar Oceanic Climate	Cfc
	Humid Subtropical Climate	Cfa
Spain	Cold Semi-Arid Climate	BSk
	Hot-Summer Mediterranean Climate	Csa
	Warm-Summer Mediterranean Climate	Csb
	Temperate Oceanic Climate	Cfb
	Humid Continental Mild Summer, Wet All Year	Dfb
	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Tundra Climate	ET
	Humid Continental Climate - Dry Cool Summer	Dsb
	Cold Desert Climate	BWk
	Hot Semi-Arid Climate	BSh
Sweden	Subarctic with Cool Summers and Year Around Rainfall	Dfc
	Humid Continental Mild Summer, Wet All Year	Dfb
The Netherlands	Temperate Oceanic Climate	Cfb
	Humid Continental Mild Summer, Wet All Year	Dfb

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Supporting the work of the MS expert group

Final report of the WP2

January, 2023

Directorate-General for Mobility and Transport
Study on road signs and road markings

SUMMARY

The Commission's Expert Group on Road Infrastructure Safety ("EGRIS"), composed of representatives of Member States (MS) and the Road Markings and Signs Subgroup, was set up to advise and assist the Commission in improving the legibility and detectability of road markings and signs, both for human drivers and for automated driver assistance systems. Approximately every two months, an EGRIS meeting was held to present key findings and overall progress of work agreed upon by contract in the area of road markings and signs. Every meeting improved the discussion and contributed to define the direction of the Study on common specifications for road markings and signs. In between these meetings, the subgroup held regular meetings with the expert chair MS to discuss various topics, such as preparing the agenda, identifying and inviting relevant experts on a particular topic, preparing relevant meeting documents and meeting materials, elaborating appropriate methods, and the like to better prepare every EGRIS meeting and ensure their successful outcome.

The main activities covered by this WP2 include:

- Supporting the Commission in preparing EGRIS meetings and meetings of its sub-group 1 "Road Markings and Signs"
- Preparing relevant information and input for the meetings and the work of the expert group
- Complementing the findings and results of each meeting and drafting a report on the final findings and conclusions of the expert group
- Consulting with the relevant bodies of the UN Economic Commission for Europe.

All findings, arguments and results from the meetings, as well as main conclusions and viewpoints, were documented and finally presented in this report. Relevant bodies and external stakeholders were also involved in the meetings and their views and suggestions were considered.

CONTENT

1. INTRODUCTION

On 10 December 2020, the European Union represented by the European Commission and the Consortium comprising the University of Zagreb – Faculty of Transport and Traffic Sciences (lead partner), University of Hasselt – Transportation Research Institute, Graz University of Technology – Institute of Automotive Engineering and AKKA I&S signed a contract to produce the "Study on common specifications for road markings and signs". Due to changes regarding the start date of the project and specific requests from the EGRIS group, the originally planned schedule was adjusted to allow the Consortium to respond to the above changes and requests and to properly carry out the necessary work. In total ten meetings were held with the participation of Member States. Several sources of relevant input were prepared for each meeting with the Commission's Expert Group on Road Infrastructure Safety ("EGRIS"), which, together with the findings and results from the previous meetings, fulfilled some of the set objectives. In addition, the Consortium worked continuously on the preparation of a report comprising the final findings and conclusions of the expert group and consulted with the relevant bodies of the UN Economic Commission for Europe.

Notes were taken during all meetings, based on which minutes of the meeting were prepared. Below is an overview of all EGRIS meetings held, including the main activities that took place in each meeting, while a detailed overview of each meeting is provided in separate chapters.

Table 1 An overview of meetings and their main activities

Date of EGRIS meeting	Meeting activities
17 December 2020	• general working arrangements (setting a timeline) • presentation of the aim of the study, main demands from the study, methodology, existing situation in Member States (regulations, procedure, practices, technical standards, guidelines) • announcement of the questionnaire
24 February 2021	• the focus of WP1 and relevant references • presentation of the questionnaire's concept • presentation of the first obtained results from the questionnaire (20 countries)
15 April 2021	• presentation of the project status, progress and time plan for the next three months • presentation of 11 opportunities based on literature findings and current practices • presentation of potential recommendations
23 June 2021	• methodological approach in identifying opportunities • presentation of areas of possible interventions • announcement of steps for the next 24 months
14 October 2021	• presentation of each option for a possible intervention • presentation of sensor systems, lane detection technologies, road sign recognition system and digital maps

15 December 2021	• making decisions regarding future work • broader presentation of possible areas of intervention • presentation of MS's feedback for each area and options for consideration • presentation of additional options for consideration • presentation of the next steps
28 February 2022	• overview of conclusions from the previous meeting • presentation of the cost-benefit methodology • presentation of the next steps – broader cost-benefit analysis
10 June 2022	• a comprehensive overview of the areas realised and conclusions reached • presentation of conclusions for each area of intervention • presentation of the initial and final proposal for cost-benefit analysis • comments and reviews from each MS representative on the concluded area
20 October 2022	• presentation by the Vice President of the European Union Road Federation (ERF) on CAV and lane markings • contractor's presentation on cost-benefit analysis, the application area (target crashes, time horizon) and main components (costs, benefits) as well as their calculation • presentation of the obtained general results • feedback on the presented work from each MS • presentation of the alternative approach (break-even cost-benefit analysis) • presentation by Paul Carlson on MUTCD changes and minimum pavement markings retroreflectivity standards that have recently been implemented in the US • general questions, suggestions and opinions by MS representatives
21 November 2022	• presentation of social cost-benefit analysis • constructive comments and discussion by some MS representatives • conclusions on certain points regarding road markings • overall conclusions on the presented work and report

2. FIRST MEETING/S (17 DECEMBER 2020)

EGRIS meeting

Although the first EGRIS meeting was originally scheduled to be held at the Albert Borschette Conference Centre in Brussels, due to the pandemic situation it took place virtually via videoconference. The first meeting was held on 17 December 2020, preceded by a kick-off meeting that took place on 14 December 2020. At the kick-off meeting, the Consortium was presented to the Commission, along with the topic of the study and the planned working arrangements. A few days later, at the first EGRIS meeting the Consortium was introduced to all EGRIS members, MS representatives and everyone present. In the first part of the meeting, Austria's practices, procedures, technical standards and guidelines in the field of road marking and signs were presented. This was followed by a presentation of the Report on implications of road markings for machine vision provided by Austroads. The focus of the meeting was the Consortium comprising the University of Zagreb – Faculty of Transport and Traffic Sciences, University of Hasselt – Transportation Research Institute, Graz University of Technology – Institute of Automotive Engineering and AKKA I&S, who presented their general work and planned activities for the production of the study on common specifications for road markings and signs. Issues raised related to the presentations concerned the level of automation and visibility requirements for road markings and signs. The general conclusion of the meeting was that the Consortium will distribute a questionnaire to obtain information on current practices and standards in Member States, which will be of great value to the future work on the study. Experts from the automotive industry and their associations were also invited and encouraged to help with their expertise. The meeting ended in an agreement that, despite the delay in starting the work, the Consortium will have set deadlines and gather initial information from Member States through a questionnaire by the next meeting.

Plenary meeting

Immediately after the first EGRIS meeting, the first plenary meeting was held on the same day without a detailed agenda. The aim of the meeting was to present the general layout of the questionnaire prepared by the Consortium and receive comments. While presenting the main parts of the questionnaire, the Consortium emphasised the need to gather feedback from Member States and information about their current standards and practices regarding road markings and signs as well as common weather and atmospheric conditions, maintenance practices and driver assistance technologies available in their countries. The Commission supported the preparation of the questionnaire and its structure and concluded the meeting by pointing out key dates for receiving the completed questionnaire and its results.

3. SECOND MEETING/S (24 AND 25 FEBRUARY 2021)

EGRIS meeting

The second EGRIS meeting was also held virtually via videoconference on 24 February 2021. After initial arrangements regarding the agenda, an overview of the minutes of the previous meeting and updates about the Consortium’s questionnaire, some MS representatives presented their practices, standards and the existing regulatory framework in their countries. In addition, the French representative presented the durability testing methodology, quality assessment objectives and maintenance costs, the ASECAP representative presented the association, and the CENELEC representative highlighted the interaction between road markings and connected automated vehicles.

The purpose of the meeting was to provide insight into the preliminary results and the structure of the Consortium’s questionnaire, which will serve as a basis for further production of the study. While presenting the main findings from the literature, the participants highlighted requirements for road markings and signs for human drivers. The main focus of the meeting was for the representatives of other Member States to give their opinion on the structure of the questionnaire and to provide accurate information on their current practices in the field of road markings and signs. The Consortium emphasised that the results of the questionnaire were preliminary, and it left room for other Member States to express their views, recommendations and other areas for consideration. In this context, the Commission concluded that the focus of the meetings was to get the most comprehensive overview of the current situation and to understand the value of common work.

Plenary meeting

The plenary meeting was held on 25 February 2021, with only Member States in attendance. The meeting opened with the topic of timetable and the definition of primary roads, followed by a discussion. Some representatives emphasised problems they have in defining general costs for all roads. The central part of the meeting was reserved for the Consortium’s presentation of the main results of the questionnaire and the main points of discussion. Questions and comments that triggered discussion came from the French representative, who expressed concern about the purpose of the work, the value of retroreflectivity, the status of road markings (existing or renewed) and maintenance in general. At this point, the Consortium clarified the values and results presented, stating that the only results obtained were responses from the questionnaire. The discussion continued on the minimum values of road markings retroreflectivity and their width, and on the type of road to which certain data refer. The Commission ended the discussion by asking for patience regarding the results and values presented, saying that there was too little information at this point to decide whether to adjust the infrastructure or the vehicles.

4. THIRD MEETING/S (15 AND 16 APRIL 2021)

EGRIS meeting

The third EGRIS meeting was held virtually via videoconference on 15 April 2021. After an initial overview of the previous meeting, the ASIMOB representative presented problems from the real environment (rain, shadows, different lighting, etc.) related to human drivers and ADAS systems. Also, different colours and sizes of signs were highlighted as possible obstacles in automatic detection. The participants emphasised several times that creating a common understanding between the industry and the authorities is what is really important for the meetings and the overall study. One of the constructive suggestions made by MS representatives was the consideration of signs that are not part of the Vienna Convention and new signs that, however, need to be harmonised. The central part of the meeting was reserved for presentations by individual members of the Consortium. The focus of the meeting and the Consortium's presentation were the (main) literature findings in the field of road markings and signs and the main objectives of the Work Package 1 (WP1) that had already been carried out. An overview of current standards and practices in Member States (questionnaire analysis) was then presented, along with some defined opportunities. The proposed opportunities that were the subject of discussion are listed below:

1) Increase the use of durable materials with increased visibility in wet conditions

2) Define common minimal levels for daytime visibility of road markings

3) Define minimal levels for night-time visibility of road markings for motorways and primary roads in dry conditions

4) Define minimal levels for night-time visibility of road markings for motorways and primary roads in wet conditions

5) Define the minimal width of road markings on motorways and primary roads

6) Use of contrast road markings to increase contrast on concrete roads

7) Properly remove old road markings

8) Define common minimal dimensions of warning, prohibitory and mandatory road signs on motorways and primary roads

9) Define a minimal class of retroreflective materials for road signs on motorways and primary roads

10) Establish digital maps of road signs

11) Improve the maintenance of road markings and signs.

The proposed options sparked concern, interest and disagreement in some Member States, leading the Commission to clarify that the entire project and study was not about creating a best practice, but about considering literature findings and current practices in MS. The conclusions from the meeting were that a decision will be made in June on whether to continue the ongoing work, that there is much work to be done before then, and that the June deadline is only a starting point for further work. All MS were pleased to provide any information they have or will have on measures, recommendations, current practices, other literature findings, etc. In the end, it was announced that the cost-benefit analysis would be done only for the approved options.

Plenary meeting

At the very beginning of the third plenary meeting, which took place on 16 April 2021, the task of the Consortium was clearly emphasised, and it was pointed out that not all questions were expected to be solved and answered until the next meeting. It was also clearly stressed that the measures are still in a discussion phase and not in the finalisation phase. In addition, the decision on the cost-benefit analysis has not yet been made because the measures with the greatest impact have not yet been defined. The main part of the meeting was reserved for the Consortium's presentation on the results of the questionnaires from 24 countries. The Consortium presented the general schedule for the next three months, the project status and progress. Numerous references collected from the available literature served as the basis for the analysis. After presenting 11 proposed options, the Consortium underlined the need for more comprehensive research and data collection. The French representative expressed his concerns about the evidence for some options and proposed opportunities. He said it was questionable whether it was the right decision to set the minimum retroreflectivity value for night-time visibility at 50 $mcd/lx/m^2$ when the literature suggests 20 $mcd/lx/m^2$. At the same time, some countries have 50 $mcd/lx/m^2$ and others have 35 $mcd/lx/m^2$. In addition, some MS representatives expressed concerns about the presentation of the data.

Discussion about mentioned values took over the meeting until the Commission stressed the real focus of the meeting, which was to discuss opportunities and not values itself. The conclusions of the meeting were that it is important to decide by June whether it is possible to start working on a set of technical specifications and to pursue further analysis and define common approaches and the content of the measures.

5. FOURTH MEETING/S (23 AND 30 JUNE 2021)

EGRIS meeting

At the fourth EGRIS meeting, held on 23 June 2021, many important issues from previous meetings were discussed and clarified. All MS representatives, the Consortium, and external observers and stakeholders attended the meeting and offered constructive recommendations. At the beginning of the meeting, the ACEA representative gave an overview of real problems identified on Brussels roads in terms of infrastructure and road signs. Insufficient preparation of roads to meet the requirements of new vehicles was mentioned as one of the main obstacles in the field of autonomous vehicles. Three dimensions of problems were presented, including physical signage, the accuracy of information obtained through the navigation system, and the location of certain signs (those for speed reduction). The main challenge for autonomous vehicles on existing roads was the detection of the signs by a camera. Next steps were defined for further analysis to identify the best possible options. These steps include:

- research review based on the literature review and current practices from the perspective of human drivers and ADAS systems
- areas for potential intervention.

The goal of the first phase of work covered by the meeting was to assess whether there were potential opportunities. This was done through a qualitative assessment for each attribute in different areas for intervention. The assigned scores for each category were explained in detail, which helped to identify a rough cost estimate, the complexity of implementation and evaluation, and the potential positive impacts under different weather and other road conditions. The meeting focused on joint work at the EU level, so a caveated cost analysis was expected. Potential areas for constructive discussion in the main part of the meeting included durable materials, daytime visibility, night-time visibility, rain, road markings width, contrast on concrete roads, proper removal of old road markings, uniformity of road markings (design, continuous line at exits or intersections, dashed longitudinal road markings) and also recommendations for the current situation in MS and potentially useful improvements for ADAS systems and human drivers. One of the most important comments from an industry perspective was about physical infrastructure, which is currently the priority in terms of detection, rather than digital infrastructure. Germany proposed the methodology, in a way that blended findings from the literature and current practice in MS. Another proposal concerned the separation of permanent materials and road markings type II. Interest was expressed in a cost-benefit analysis, although it was known that this was difficult to do at this stage of the research. Further, the relationship between road crashes and poor quality of road markings was mentioned as an important element to consider when making recommendations for contrast ratio and minimum daytime visibility values for road markings. The Commission expressed its intention to continue the cooperation with the automotive industry and expressed hope to achieve the most positive result possible. The meeting ended with the conclusion that the intention is not to intervene by inventing new signs or changing the content of the existing ones, but to make the signs more visible and recognisable without changing their content.

Plenary meeting

On 30 June 2021, the fourth EGRIS plenary meeting was held via video conference, where all MS were glad to provide comments on the study. The meeting covered the evaluation methodology and methodological approach, along with the following steps for the next 24 months. The biggest concerns expressed by some MS representatives were about the methodology and approach itself, as well as industry requirements that had not been heard before. The goal of the meeting was to come to a common conclusion and decide whether to conduct a cost-benefit analysis before more detailed work is done. Some MS representatives expressed concern about the proposed values and suggested an additional assessment of the proposed options to be conducted by MS to provide more clarity. At the end of the meeting, it was decided that a timeline would be developed for the next three months, focusing on the first phase, and that the subgroup would continue working on the study to develop different options for different areas of intervention.

6. FIFTH MEETING (14 OCTOBER 2021)

Plenary meeting

The fifth meeting of the EGRIS Plenary Group was held on 14 October 2021 virtually due to the ongoing pandemic. The beginning of the meeting was reserved for the questionnaire. In other words, each area of the questionnaire was presented together with the feedback from Member States (13 MS and Norway). The main conclusions for each area were as follows:

- Area 1: Increasing the usage of durable materials with increased visibility in wet conditions is important. Furthermore, it is more important to look at the performance level than the material itself.
- Area 2: There is an explicit request for establishing a correlation between minimum threshold and crashes. It is questionable how ADAS systems actually function due to deficiencies in road markings.
- Area 3: Possible options for establishing minimal night-time visibility for new road markings on motorways need to be investigated. It is necessary to discuss weather conditions in relation to other areas rather than to road network. The influence of the climate and amount of traffic on roads need to be taken into consideration for the minimum levels for old road markings.
- Area 4: Not defined due to extensive discussion about specific materials which can be used for achieving certain levels for wet conditions.
- Area 5: Discarded area for further work due to the fact that MS found it difficult to measure the quality of road markings and to apply a correct method.
- Area 6: Further analysis should focus on the correlation between minimal width of road markings and crashes, respectively road safety outcomes and budgetary considerations.
- Area 7: There is insufficient evidence in Member States regarding this area, based on current standards and practices applied. The area will not be further analysed.
- Area 8: Guided by the fact that most Member States use asphalt roads and that there is insufficient evidence about improved detection quality for ADAS, it was decided not to further explore this area.
- Area 9: Since current road markings cannot be removed perfectly, and it is difficult to define the remaining traces, it was concluded not to further explore this area.
- Area 10: Based on the responses from Member States, different standards and practices among them and international convention and law, it was decided not to further explore this area.
- Area 11: It was decided to rule out the mentioned area from further research due to unclear evidence for ADAS/human drivers in terms of configuration of dashed longitudinal road markings and since MS have different standards and practices.
- Area 12: MS practices regarding minimal dimensions of warning, prohibitory and mandatory road signs were discussed.

- Area 13: Most Member States use minimum class II (RA2) for road signs, both on motorways and primary roads. It was proposed to look at other factors such as lighting conditions and the position of the sign when considering road signs retoreflectivity.

- Area 14: There are possible options to be investigated in the field of digital maps of road markings and signs.

- Area 15: It was clarified that this topic (improving the maintenance of road markings and signs) is out of the scope and that further discussion is not needed.

Member States commented and discussed each area, and their feedback was taken into account before reaching the final conclusions presented above. The overall conclusion of the meeting was that certain areas need to be researched and discussed more in future meetings while others can be ruled out.

7. SIXTH MEETING (15 DECEMBER 2021)

Plenary meeting

The sixth meeting of the EGRIS Plenary Group took place on 15 December 2021 virtually due to the ongoing pandemic. According to conclusions from the previous meeting, certain areas were ruled out and the meeting focused only on some areas, as follows:

- Area 1: Performance of road markings on motorways
- Area 2: Daytime visibility of new road markings
- Area 3: Night-time visibility of new road markings in dry conditions
- Area 4: Night-time visibility of new road markings in wet conditions
- Area 5: Width of road markings
- Area 6: Dimensions of warning, prohibitory and mandatory road signs
- Area 7: Implementing minimal class of retroreflective materials for road signs
- Area 8: Supporting the development of accurate digital maps of road markings and road signs.

Each presented area was thoroughly discussed by the Commission and the Member States. The discussion resulted in the following remarks and conclusions:

Area 1: It was agreed to carry out the analysis and try to find different options not related to the type of the material but rather to the performance of the material (visibility). It was proposed not to pay too much attention to the mechanical durability (material types, technologies) of road markings, but to focus on their visibility and detectability.

Area 2: It was decided not to impose requirements for the whole lifetime of the infrastructure but only at the beginning when road markings are implemented. It was recommended for each MS to propose the minimum value for daytime visibility of new road markings which will be suitable for the functionality of ADAS. The overall conclusion was that 160 mcd/lx/m^2 may be too high for the needs and that most countries preferred 130 mcd/lx/m^2. At this moment no decisions were made and only options were considered, including the needs of automated vehicles.

Area 3: Based on current practices in MS and literature, several options were proposed for consideration about including minimal level of retroreflectivity. The proposed values to be set were 1) 300 mcd/lx/m^2 for motorways and 200 mcd/lx/m^2 for primary roads, 2) 300 mcd/lx/m^2 for motorways and 150 mcd/lx/m^2 for primary roads, and 3) 200 mcd/lx/m^2 for motorways and 150 mcd/lx/m^2 for primary roads. Another option is to consider 200 mcd/lx/m^2 both for motorways and primary roads.

Area 4: Presented options for consideration in this area included the same minimum values of 50 mcd/lx/m^2 for both motorways and primary roads or 35 mcd/lx/m^2 for both motorways and primary roads. Another proposed option was to set different minimum levels for motorways and primary roads which would be 50 mcd/lx/m^2 and 35 mcd/lx/m^2 respectively.

Area 5: The minimal width of 15 cm for centre lines and 20 cm for edge lines on motorways were set as some of the proposed values in this area. The second option was to apply the minimal width of 12 cm for both centre and edge lines on primary roads. Due to different speed and design characteristics in motorways, a common approach for both types of roads was not suggested. After received comments and opinions, it was concluded that it is possible to apply minimum 15 cm wide road markings both on motorways and primary roads but to further analyse the effect of 20 cm wide road markings.

Area 6: There were two options for consideration in this area. The first one included warning signs (triangle shape) to be at least 120 cm for motorways and 90 cm for primary roads and warning signs (circle shape) at least 90 cm for motorways and 60 cm for primary roads. The second one included warning signs (triangle shape) to be at least 100 cm for motorways and 90 cm for primary roads and warning signs (circular shape) to be at least 90 cm for motorways and 60 cm for primary roads. The most significant conclusion was that there is currently no proof that 120 cm is better than 100 cm as a road sign dimension, so this area will not be further analysed.

Area 7: It was proposed to apply at least class II (RA2) signs on all motorways, class III (RA3) signs for speed regulation on motorways and class II on primary roads.

Area 8: Proposed measures are to be discussed at the next meeting which colleagues from the ITS will be attending.

In addition to each area discussed, an overview of perception sensors, lane detection technologies, road sign recognition systems and digital maps were explained in relation to camera technologies. Methods related to road signs recognition system were thoroughly presented along with benefits and challenges concerning ADAS. The meeting focused on future challenges which include sign harmonisation, maintenance (damaged signs), maintenance in the process of digitisation, design patterns and digitisation in general. One of the main challenges for current and future vehicles presented was the recognition of road signs placed on different objects, such as school buses. Removing old road markings and electronic speed limits were also mentioned as challenges.

The final part of the meeting included feedback and comments from each Member State on the areas presented. The performance-based approach was very much welcomed by Member States, but some major concerns were also expressed, such as the relationship between skid resistance and visibility. Member States expressed a desire to provide input before discussing policy options. Area 2 elicited many responses from Member States, some of which commented on the proposed values, other values to be considered, and the contrast ratio. Opinions on the mentioned range and values varied, but most MS claimed that 130 mcd/lx/m^2 is an appropriate value for daytime visibility of new road markings. Although different countries set different values for the minimum value of retroreflectivity for night visibility of new road markings in dry conditions, the general conclusion and value proposed by most countries was 150 mcd/lx/m^2. The minimum value for night visibility of new road markings in wet conditions proposed by most countries was 35 mcd/lx/m^2, which should apply to both motorways and primary roads. Regarding the width of road markings, MS proposed different options. Some of them proposed a width of 15 cm for edge lines on motorways, while others wanted a width of 15 cm for centre lines and 20 cm for edge lines on motorways. The width of lane markings on primary roads was generally accepted as narrower (12 cm) than on motorways.

Apart from road markings, important topics were also proposed regarding road signs. With respect to the future of the automotive industry, the technology and the sensors for new vehicles, the issue is the dimensions of warning, prohibition and mandatory signs that need to be standardised among Member States. Although some countries did not see any advantages in harmonisation, the general opinion was that countries in any case already apply the rules of the Vienna Convention, which are sufficient in most situations. Although there was an opinion and a suggestion that some signs, such as speed limit signs, should be made of higher quality material, almost all Member States agreed that these signs are not that much more important than others. In addition, Member States felt that class II signs are sufficient for general use on motorways and primary roads, while class III material would be more appropriate in exceptional cases. Another important concern was that it is important not to set too high requirements in low volume unlighted roads because in such conditions low retroreflection is feasible and too high retroreflectivity may cause glare. The biggest disadvantage in the field of road signs and their position near the road is the lack of adequate literature findings to support decisions regarding this matter.

The general conclusions of the meeting were drawn separately for each area discussed. For Area 1 (performance of road markings on motorways), it was decided that further research would focus on performance, i.e., visibility, and leave decisions on durability and materials to Member States. For Area 2 (daytime visibility of new road markings), it was decided that further research is needed, as well as more feedback from Member States to define a minimum level of Qd. Another option was proposed for Area 3 (night visibility of new road markings in dry conditions) – 150 mcd/lx/m^2 for both motorways and primary roads. For Area 4 (night-time visibility of new road markings in wet conditions), 35 mcd/lx/m^2 was further evaluated and compared to 50 mcd/lx/m^2. For Area 5 (width of road markings), Member States agreed on a minimum width of 12 cm for primary roads and 15 cm for roadside markings on motorways. For Area 6 (dimensions of warning, prohibition and mandatory signs), it was concluded that there are insufficient supporting findings for further action at the moment. Similarly, for Area 7 (implementation of the minimum class of retroreflective materials for motorway signs), it was concluded that the benefits of moving from class II signs to class III signs are not well documented. For Area 8 (supporting the development of accurate digital maps of road markings and road signs), it was decided that additional support is needed from experts at ITS.

8. SEVENTH MEETING (28 FEBRUARY 2022)

Plenary meeting

The seventh consecutive meeting, attended only by MS representatives, took place on 28 February 2022 in the form of a video conference. The focus of the meeting was the methodology of the cost-benefit analysis (CBA), which will be carried out in the near future.

The first part of the meeting was reserved for the contractor's presentation on the scope, measures, approach and limitations of the CBA. The CBA method and approach were explained in detail, focusing on the night-time visibility of road markings in dry and wet conditions, as well as in dry daytime conditions. The highlighted aspect of the proposed calculation involved both human drivers and ADAS, based on the "weakest link" scenario that occurs for humans at night (in wet and dry conditions) and for ADAS in daylight. In both cases, the "weakest link" was also the width of the road markings. The costs, as a very important part of the analysis, need to be combined with all the costs of different companies and with average values. As for the constraints, data quality was highlighted as the key, while crash data (for the last five years), crash cost, crash cause change factors, lane-keeping system impact, and lane-keeping system penetration rate were mentioned as key parameters to evaluate the benefit components.

The central part of the meeting was a detailed discussion of the overall approach and the planned methodology for continuing the work. The main concern regarding the approach described was the data on crashes related to the quality of road markings. Several Member States expressed concern that only 5% of crashes were related to road markings, while the rest were due to speed, wet road conditions, slippery roads, etc. In addition, the purpose of a CBA, in general, was questioned since the quality of road markings is better in some countries than in others. Furthermore, some MS proposed to compare crashes among MS with different visibility values and use them to calculate the CMF. The Consortium did not accept the proposed approach, considering it insufficiently scientific. In addition, MS representatives made several suggestions, namely observing the situation in MS where certain values already apply, combining two observations and applying the reduction factor, and developing a method applicable to some parts of the network and not to the whole network. MS representatives expressed the opinion that the costs were underestimated, and the benefits overestimated, and that the analysis is meaningless if it is assumed that all measures will have a positive result. Both the Consortium and the Commission emphasised the limitations of the analysis and their awareness that certain benefits are overestimated and certain costs underestimated, but this is due to the lack of accurate data. Overall, the focus of the study is to help all MS to improve their system. Since the discussion did not progress in any way, the Commission stated that if there is no agreement on the methodology, there is no way to move forward.

Finally, the decision was reached to implement a new approach and methodology was presented along with confirmed studies, cost-benefit analysis and feedback from all MS.

9. EIGHT MEETING (10 JUNE 2022)

EGRIS meeting

One year after the first EGRIS meeting held in June 2021, the second one was held on 10 June 2022. After many comments, feedback from MS, thorough discussions and views from previous meetings, it was decided that further work will concentrate only on road markings. Areas that previously included road signs were excluded at this meeting, which caused concern among some representatives of the automotive industry. Areas that should be discussed in more detail regarding road markings include:

1) Common minimum daytime visibility standards for new white road markings
2) Common performance standards for road markings
3) Common minimum night-time visibility standards for new white road markings in dry conditions
4) Common minimum night-time visibility standards for new white road markings in wet conditions
5) Common minimum width of road markings.

Based on feedback received from MS, it was decided that mechanical durability and performance material will be set aside when looking into minimal levels of visibility of new road markings. The whole idea was to establish minimum performance levels and to leave the decision on material type to each MS. When it comes to Area 2, it was decided to set an optimum performance level for road markings according to the literature and practices, which is the same for primary roads and motorways (min Qd-160 mcd/lx/m^2 or min Qd-130 mcd/lx/m^2). Regarding common minimal levels for night-time visibility of new road markings in dry conditions, many possible solutions for applying minimum values were proposed. For night-time visibility of new road markings in wet conditions it was concluded that both 35 and 50 mcd/lx/m^2 on primary roads and motorways will be taken into account for running a cost-benefit analysis. For Area 5 (width of road markings), three options were taken into account, namely separate minimal widths on motorways for centre and edge lines, the same minimal width on motorways for centre and edge lines, and minimal width for primary roads.

The contractor emphasised the set goal of the entire study and the cost-benefit analysis, which includes achieving common values of costs and benefits for new road markings on motorways and primary roads. These values should be set for both human drivers and ADAS. The proposed values are set based on feedback from MS and the results of questionnaires collected from MS at previous meetings. The contractor emphasised once again that the proposals do not refer to road marking material to be used by each MS. Parameters used for the cost-benefit analysis included variables such as target crash type, crash modification factor and crash cost per crash type. Overall, the existing limitations were pointed out several times, so all MS representatives are aware of them. Since there were many misunderstandings and rejections of the proposed CBA at previous meetings, a Norwegian study was presented with an example and drawbacks. The rest of the meeting included a presentation by each MS, giving the main overview of their network along with the minimum quality thresholds for each type of visibility.

Austria is currently testing various road markings for durability to achieve higher limits or indicators. Since Austria is mainly an alpine country, and because of snowploughs, more than 50% of road markings have to be renewed in this country every year.

Belgium, on the other hand, conducts various tests to verify the performance of the observed road markings over time. The country does not set specific values for new road markings. Overall, the main disadvantage of textured road markings was said to be their property to generate noise, which is particularly problematic in urban areas.

After the introductory part about the general facts and the length of motorways and national roads in France, a durability test method was presented as part of French research. The durability test in France relates to the visibility of road markings (at night) in rainy and wet conditions.

Ireland presented the calculation of costs and the results obtained for different road markings. They pointed out that road markings should be tested regularly so that their quality can be observed. Performance-based contracting delivers quality over time and was highlighted as a good approach for road users, taxpayers and contractors. The main concern from an Irish perspective was the maintenance of road signs and their life cycle.

Sweden pointed out problems in northern countries, which include studded tires due to weather conditions. With this in mind, they highlighted rumble strips as the best option when it comes to taking higher safety measures.

In the Netherlands, all stakeholders (road authorities, police, knowledge institutes, etc.) are involved in decision-making regarding road markings standards and specifications and the application of new guidelines.

Germany defined recommendations for the renewal of road markings, but the minimum technical requirements for road markings are the same on motorways and on rural roads. Although they have the same requirements, various materials are used for road markings in Germany, e.g. cold plastic (spray plastic), thermoplastics, paints and adhesive tapes. Germany expects that the quality of road markings on all roads in the country is and will remain high.

After the Member States, industry representatives presented what they consider to be the requirements for motor vehicles in terms of road marking materials and the overall quality of road markings. After having presented international practices, they pointed out facts about processes related to machine vision. Australia was highlighted as a country that did well in that sense. In their view, 150 mm wide markings and a minimum visibility of 150 mcdlx-1m-2 ensure an acceptable level of roadworthiness for future cars. On the other hand, "all-weather" road markings used in work zones in the U.S. have been identified as one of the most important measures to increase road safety. Overall, the visibility of road markings, which is affected by many factors, is very important, so a safe system approach is needed to achieve a high level of road safety.

Despite the imperative of road safety and the necessary measures to achieve the above objectives, costs always play an important role in the decision-making process for implementing the right measures. In this context, lifetime in some countries was presented as a challenge due to winter maintenance, traffic density, position of road markings, surface conditions, etc. Another issue is labour and traffic management costs, which are not comparable in Western and Eastern European. For these reasons, it was clearly emphasised that many things need to be considered when preparing guidelines.

Regarding the work presented, issues were raised about maintenance costs and how they might be reduced in the future in light of requirements for the next generation of sensors and future vehicles. Concerns were expressed about the relationship between road markings and road safety in terms of cost, as higher investments are needed for achieving better road markings and overall road safety. Lane-keeping assistance was highlighted as an important feature that needs to be applied to all vehicles and which requires good quality road markings.

The results of tests conducted with the Mobileye camera were presented to everyone present. It was confirmed that Mobileye detects road markings better at night than during the day when there is ambient light, glare and various visual obstacles. Stressing the poor quality of road sign infrastructure and the fact that good infrastructure saves lives, some industry representatives said it was important not to exclude this issue from the discussion. Concerning crashes, it was noted that they are never caused by just one factor, so they cannot be studied only through the aspect of retroreflecting road markings.

The whole meeting concluded that many countries use guidelines for road markings and there are a lot of elements that need to be considered (calculations and traffic management at national level). Also, all countries focus more on performance than on materials for road markings, which is the right way to move forward in the study. Regarding prices, it was left to the Commission to decide on this matter given the current situation in Europe.

Plenary meeting

The eighth plenary meeting was held on 10 June 2022 in a hybrid version, with some MS representatives attending the meeting live while others followed the agenda online. This plenary meeting took place directly after the EGRIS meeting, which was held on the same day but in the morning.

The first cost-benefit proposal presentation, given by the contractor, focused on proposals for new road markings on motorways and primary roads. Among the measures highlighted were road markings visibility (at night – dry and wet, during the day – dry) and their width. To be more precise and clearer, the contractors attempted to explain that there will be limitations in the study, such as crash data, CMFs, road network, cost, etc., and that a cost-benefit analysis can only be performed for the cases for which sufficient data are available. To avoid repeated questions about the cost component, crashes, and calculation of the CMF, the Norwegian study was presented in detail using a break-even analysis. While explaining the calculation of costs based on fatalities and injuries, the costs for each MS were highlighted to provide a cost assessment. In this way, the break-even analysis is intended for estimating the incremental cost of the intervention (increased width of road marking, different visibility) and calculating the effectiveness of the intervention. The contractor's presentation focused on the benefits of the proposed approach, which the MS representatives accepted more readily than in the previous cost-benefit analysis.

The purpose of the meeting was to decide whether there was enough support to proceed with the work. Thus, it was up to MS to comment on whether there was a strong case for continuing the work.

It was decided that the work will continue successfully, and that the future work of the contractor will be discussed with the Commission, taking into account the European level and the average values for the visibility of road markings in all MS. Norway’s contribution with the break-even analysis was very helpful for further progress of the study. The positive outcome of the Norwegian approach presented and proposed is that the methodology can be applied to both fatal and other types of crashes.

10. NINTH MEETING (20 OCTOBER 2022)

EGRIS meeting

After the summer break and an extended period of active work on the study, the next EGRIS meeting took place on 20 October 2022. The meeting was held in a hybrid version at the Albert Borschette Conference Centre Room 0C and online. The focus of the meeting was the cost-benefit analysis of the Consortium, based on the previously agreed principles of Member States. Another important contribution to the meeting was made by experts Harald Mosbock and Paul Carlson, whose presentations cleared up many ambiguities and doubts regarding the application of the proposed rules, guidelines and laws.

The first part of the meeting was reserved for the presentation of Mr Mosbock (Vice President of the European Union Road Federation (ERF)), which focused on the Manual on Uniform Traffic Control Devices for Roads and Motorways (MUTCD), the minimum width of road markings of 6" (15,24 cm) and the minimum retroreflectivity values for longitudinal road markings (on roads with a speed limit of 35 mph or more – 50 mcd/lx/m^2 and at least 100 mcd/lx/m^2 on roads with a speed limit of 70 mph or more). In addition, retroreflectivity practice according to the Australian study was presented, as well as the level of automation in Japan and the standards applied in China.

The contractor presented the following step and stressed the importance of future work and research regarding the cost-benefit analysis for new road markings. The cost-benefit analysis is to be carried out according to the Norwegian approach, which Member States endorsed at the last meeting. Following this approach, the cost-benefit analysis included the scope (target crashes, time horizon) and the main components (costs, benefits and their calculation). Costs (material costs) were based on a four-year time horizon, while benefits (costs saved) included fatal injuries, serious injuries and minor injuries in single-vehicle (non-drunk driving) crashes on motorways and primary roads in specific Member States. The Consoritum also highlighted the benefits of road marking measures related to certain visibility levels and widths. One of the key points was that the analysis does not specify which Member State should use which type of material. Other details of the analysis included assumptions for Member States that have not yet reached the common minimum visibility values, and a trade-off was also considered for those Member States that have two or three values for road marking visibility or width. Mentioned limitations included results on specific parameters. General results were presented for six Member States that currently have lower values for road marking visibility and width than the recommended minimum values. Calculations of specific values for motorways were not performed because the data were not available. The presented results include cost per fatality, cost per serious crash and cost per minor crash, and they were followed by a proposal for further research.

The second part of the meeting dealt with reactions to the presented work from almost all Member States.

Austria expressed concern about the high value of retroreflectivity without additional investment in contrast markings, and Germany joined with additional concerns about the calculated cost-benefit ratio. The reaction was triggered by the situation in Germany, where half of the motorways have small lanes and half of the motorways have wide lanes, which in the German view makes no difference. In addition, the methodology was said to be questionable because no data was provided on the width of lane markings and related crashes, raising the question of how the cost-benefit ratio can be changed with certainty if these data are not available. The contractor explained the mentioned obstacles by providing data from Member States based on which it performed the calculations. The fact that some data were missing or were not received data from some Member States was a limitation of the calculations, so the respective Member States were asked to provide these and any other important data they have until the next meeting.

From the Bulgarian point of view, the width in terms of visibility of road markings was questionable and not entirely correct. It was pointed out that widening the lane markings makes the road narrower, which may ultimately lead to greater safety, as drivers tend to drive at slower speeds in such situations. Other concerns expressed by the Bulgarian representative related to more specific values that were not provided at this time, and he also expressed hope that the overall goal of the study will be achieved. According to the contractor, the proposed method for considering the width of road markings requires the use of a crash modification factor, which was not approved at the last meeting. For this reason, the cost could not be calculated in the manner proposed.

Positive feedback came from Cyprus, which looks forward to future crossings and technologically advanced transportation where road markings will play a more important role. Italy suggested sharing data among other expert groups (Consortium), which could be beneficial for future work.

Differences among Member States became obvious in crash costs, which vary greatly among MS (some of them use excessively low values for cost-benefit calculations, like Hungary), which ultimately makes it difficult to implement the same construction measures in all MS. Against this background, Hungary drew attention to this problem.

Ireland proposed looking into countries having the same characteristics and using different types of lines and Lithuania warned about forecasting a cost analysis in countries with high inflation rates. A deeper outlook on other types of lines and similar elements is impossible due to the lack of needed information, which was again requested from Member States.

On the issue of increasing the benefits of road markings in the future for autonomous vehicles, the contractor stressed that they were not included in the analysis because it was decided that the analysis would not include the accident-avoidance factor. Sweden stated their problem with studded tires that affect the quality of road markings. According to the Member State, these differences should be taken into account in order to meet all the requirements and propose clear and uniform recommendations. In addition, the importance of setting a minimum standard was emphasised, not only for human drivers but especially for automated vehicles, which are likely to become more common in the future. It is also important to know the minimum values that are sufficient for ADAS devices to be effective. Particular attention was paid to ADAS currently in use and the minimum requirements they can meet.

The remainder of the meeting focused on the second part of the Consortium's work, in which an alternative approach was presented along with a break-even cost-benefit analysis. In this context, the plan is to estimate the incremental cost of the intervention and thus calculate how effective the intervention needs to be to reduce a given number of crashes and injuries. It is also necessary to discuss the ethical aspects of the approach and effective interventions that should be worthwhile. The scope and differences in methodology were compared, as well as key components such as costs (implementation costs and length of median and edge line markings) and benefits (number of fatal injuries, serious injuries, and minor injuries caused by improved road marking at specific visibility levels and widths). Assumptions were described by conditions when multiple visibility levels/widths occur. This was followed by a presentation on limitations and general results. The discussion on the presented work was derailed by the fact that France uses certified products of a certain class, which raises the question of which class or type of material is more important in terms of durability and lifetime. Major differences among Member States were described, which at this stage were put aside for further consideration and discussion.

In the last part of the meeting, the presentation by Paul Carlson showed perspectives and views beyond the European Union. His detailed presentation included two interesting topics, namely 1) changes to the MUTCD – Manual Uniform Traffic Control Devices, and 2) minimum standards for retroreflective road markings recently introduced in the USA. What is unique about the MUTCD is that there were over 2,000 amendments and over 35,000 comments received prior to its adoption. The most significant changes in the manual were related to line width (recommending 6-inch lines on high-speed (over 40 mph) roadways) and exit ramps (chevron core area). In addition, Mr Carlson's presentation provided an overview of the policies, practices and general background in the US regarding road marking visibility. According to US regulations, 50 mcd/m2/lx is recommended for retroreflectivity of road markings in dry conditions on roads with speeds of 35 mph or more. Nevertheless, authorities use 100 mcd/m2/lx for high-speed roads (70 mph or more). The most important fact is that the above values do not apply to automated vehicle systems but are based on humans and human vision systems. It was emphasised that the mentioned values should apply only on longitudinal routes. Regarding maintenance, which has been mentioned several times in previous meetings, in the US this is 100% covered by FHWA and the government. The most useful part of the presentation for the ongoing study and meetings is the fact that engaging different audiences in the US by organising workshops, conferences and similar events helped to collectively reach out to professionals and the public to gather evaluations and create the best possible manuals and recommendations. The biggest obstacle was getting information from the automotive industry to find out where the real problems are so that infrastructure stakeholders can reflect on what can be done to improve.

Mr Carlson's presentation brought the meeting to a close, with a few questions, concerns and recommendations left unanswered and to be considered at the next meeting.

11. TENTH MEETING (21 NOVEMBER 2022)

The meeting which was set to be the last one in 2022 was held on 21 November in Albert Borschette Conference Centre Room 0C and online via videoconference for those who could not participate in person. Since the last meeting was not that long ago, this meeting just picked up where the previous one had left off. The purpose of the meeting was to get final thoughts, observations and opinions on the work done in the last work package. All Member States were asked to strongly support the analysis and future decisions to provide a reasonable cost-benefit framework.

In the first part of the meeting, the representative of the Consortium presented the latest contributions to the study. This was followed by an explanation of road crashes and potential benefits included in the analysis and the calculation of the cost-benefit ratio. Assumptions and constraints were considered separately. As in previous meetings, all Member States were asked to provide additional data if available so that the conclusions could be somewhat refined. The Commission also clearly emphasised the need for each Member State to provide feedback and participate in discussions. The main goal of the work being done, according to the Commission, is to help those Member States that are lagging and bring them up to the level of those that are using best practices. All the work done so far has been in line with the scope of the Directive and has focused on ADAS systems and human needs, while automation has not been touched on at all.

Some questions from MS representatives about road signs drew the attention of the Commission, who reminded them that the colleagues from ACEA were present at the first meetings and complained about every single situation on the network that is not suitable for the new vehicle technologies. To improve this, the Commission proposed for each Member State to submit a dossier with all the necessary elements it finds unsatisfactory concerning the ISA legislation so that this can be taken into account. In addition, it was strongly emphasised that the aim is not to create a database of standardised speed limit signs for the whole of Europe.

MS representatives more or less agreed to continue the work and ultimately obtain uniform guidelines. The major concerns were related to the actual CBA analysis and the break-even point in the calculation, but also the fact that smaller values were not calculated. The contractor dealt with the concerns, explaining that if a certain country already reached the threshold of 100 or 130 mcd m-2lx-1, it was not taken into consideration. It was also said that the calculations do not start from zero, but that the current situation is considered together with the values agreed upon in previous meetings.

In their comments, MS representatives reiterated that different weather conditions in the northern countries of Europe require different traffic management. Accordingly, the Commission stated that the regular renewal of road markings depends on the technical solution chosen, which has not yet been decided. On the other hand, many Member States did not provide new or additional comments on the report due to short reflection period. Most Member States approved the proposed minimum retroreflectivity values for new road markings and expressed their support. France did not fully agree, believing that some changes should be made to the data (overestimation of benefits) and that figures should be better explained. Regarding speed limit signs, it was clarified that the idea is to create a database of all possible signs in Europe and not to standardise speed limits *per se*. This statement is also based on the fact that not all signs are comparable in every country. However, most countries accept the proposal to provide more additional data, but it has been pointed out that manufacturers are reluctant to provide the needed information that would be of great importance for this study.

The general conclusions of the meeting related to the few points on road markings. The first thing was that legislation is not in the works, but there is an interest in developing guidelines. Also, certain areas need to be discussed and analysed in more detail. Cooperation was announced with the Partnership for Cooperative Connected and Automated Mobility, which is funded by all Member States (as it is funded from the EU budget). It was emphasised that the intention was to limit the work to eight areas related to road markings and signs and not to carry out any other activities. Moreover, the main idea mentioned was not to change the material of road signs, their dimensions, etc., but to be a bit more pragmatic, to see the difficulties from another perspective and to support the existing needs.

Member States were finally requested to provide a picture of their speed limits and all the conditions associated with them so that it would also be available to manufacturers for use in their systems. The last concluding thought was not to open new areas, but to strongly support the existing ones.

Technology review of driver assistance technologies

Final report of the WP3

October, 2021

Directorate-General for Mobility and Transport
Study on road signs and road markings

SUMMARY

This report proves a technology review of driver assistance technology. It builds on previous studies of the Commission Expert Group on Road Infrastructure Safety (EGRIS). The EGRIS has been set up by European Commission to support activities regarding improving the readability and detectability of road markings and road signs. The overall aim of this study is to determine the common specification for road markings and road signs that considers both human drivers and ADAS systems.

The report investigates the state-of-the-art technology behind drivers assistance systems used to read and detect road markings and road signs. First, some insights on Automated Driving are provided in order to get a better comprehension of ADAS, the different levels of automation (SAE Level 0-5), ODD and existing standards. This report summarizes the work principles and limitations of Lane Support Systems (LSS) and Traffic Sign Detection and Recognition (TSDR) systems.

LSS and TSDR are both image-based technics. Unfortunately, cameras are particularly affected by certain weather conditions (fog, snow, rain) but also lightning conditions (night, backlight in front of the cameras). Some recent studies highlight the benefits of combining other sensors such as LiDARs.

In the next 10 years, we'll see a major deployment of ADAS systems. While ADAS SAE L0-2 are already deployed and encouraged by new regulations, higher automated driving Levels (3-5) will take more time to make their place. New sensors, better connectivity and interaction between infrastructure and cars will benefit to ADAS system enabling more performant systems and improved safety on roads.

CONTENT

1. INTRODUCTION

Throughout history, people were searching for ways to explore more territory, expand influence over larger areas and travel further and faster. Centuries of development of transport technologies brought us where we are now. Today we can with ease transport people and goods over large distances by road, water or air. But advances in the transport did not come without costs. It is estimated to be more than 1.4 billion vehicles on the Earth [1] which has for consequence reduction in fossil fuel, an increase of pollution, high congestion in urban areas, approximately 1.3 million death each year and 50 million more people that suffer from non-fatal injuries [2]. To ensure sustainable transport, radical measures should be conducted. Today humanity is facing maybe the greatest changes in the history of transport and more dramatic changes are to come. Those changes can be characterized by four megatrends, electrification, shared mobility, connected mobility and automated driving [3].

Acceptance of electric vehicles increases each year. Shifting from combustion engines has the aim to decrease greenhouse gas emissions, but several challenges remain. The transition must assure a sufficient charging station, the electric capacity of a network, the driving range should further improve, and much more. The popularity of electric vehicles leads to high electricity demands, which means that renewable sources of electric energy would not be enough. To overcome this cornerstone, share mobility can offer one part of the solution. The concept of owning a car shifts towards using cars as a service. This solves the problem with traffic congestion, parking places and further contribute to transport sustainability. Many services already exist that belongs to shared mobility such as taxi services, public transportation or services of companies like Uber or Lime. To enhance the acceptance of new ways of transport and the reliability of automated driving, connected mobility comes into play. Communication vehicle-to-vehicle (V2V), vehicles-to-infrastructure (V2I) or more general vehicle-to-everything (V2X) can connect all megatrends and support the realization of sustainable transport concept.

Automated driving (AD), one of the fastest-growing application areas is maybe the most challenging of all megatrends. But also can bring many advantages like road safety, higher commuting comfort, available transport for elder and disabled people and reduce pollution by increasing traffic efficiency.

Undeniable, safety is the primary motivator for automation of transport but at the same time the greatest challenge. Although human error is the main factor in road accidents, the human driver is still an excellent controller with high perception capabilities and fast decisions. This set the high bar for advanced driver assistance systems (ADAS). Nevertheless, they show great potential in accident prevention.

Reducing fatal road accidents is a global aim supported with strategies of policy-making organs and organizations like the European Commission, UN General Assembly (UNGA). Figure 1 shows observed fatalities and EU targets over the last two decades.

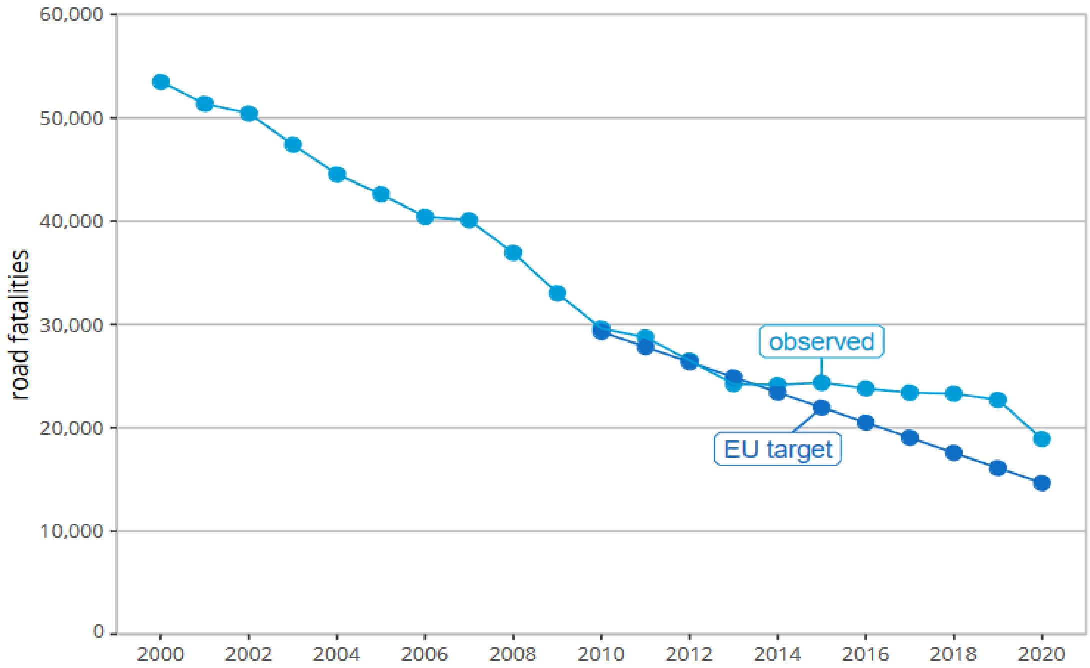


Figure 1 Observed road fatalities and EU target (Source: [4])

Despite the EU targets are not met, the underlying trend is directed downwards. The EU also adopted the Vision Zero strategy [5] that eventually aim to achieve zero fatalities and severe injuries. The essential question is what cause the accidents and how they can be prevented? The World Health Organization (WHO) recently reported on road traffic injuries [2] in which they highlighted main risk factors. Main accident factors are speeding, driving under the influence of alcohol and outer psychoactive substances, non-use or misuse of passive safety systems, distracted driving, unsafe road infrastructure, unsafe vehicles and inadequate post-crash care and law enforcement.

To help with those types of risk factors, a wide range of driver support features (SAE Level 1 & SAE Level 2) have been developed. Such support systems are adaptive cruise control (ACC), forward collision warning (FCW), lane departure warning (LDW), lane-keeping assistant (LKA), autonomous emergency braking (AEB), blind-spot monitoring (BSM), intelligent speed assistance (ISA), highway assist (ACC + LKA), park assist, traffic jam assist and much more. How much ADAS can help in accident prevention is provided in WP1 and summarized in Table 1.

Table 1 Literature overview of ADAS accident prevention

Source	System	Founding
Eichberger et al., 2011 [6]	LKA	The study shows LKA potential in accident prevention. The system would have prevented 17% of fatal traffic accidents in Austria and further enhanced it by 13%.
Kusano et al., 2015 [7]	FCW, LDW	Between 0 and 67% of crashes and 2 and 69% of moderately to fatally injured drivers in rear-end collisions could have been prevented if all vehicles were equipped with the FCW systems. The LDW-systems could have prevented between 11 and 23% of drift-out-of-lane crashes and 13 and 22% of seriously to fatally injured drivers.
Hickman et al., 2015 [8]	LDW	Results show that trucks equipped with LDW had a 48% lower crash rate for the single-vehicle run-off-road, head-on, and sideswipe crashes, compared to the trucks without LDW.

Sternlund et al., 2017 [9]	LDW	Analysis of the Swedish national statistics showed that LDW yielded a statistically significant reduction of 53 %, with a lower limit of 11 %, for head-on and single-vehicle crashes on roads with higher speed limits (70–120 km/h).
Spicer et al., 2018 [10]	AEB, LDW	Authors based their research on crashes which included BMW vehicles in the US fleet and found that vehicles equipped with ADAS were involved in, between 13 to 63 % fewer accidents (depending on vehicle type and crash type).
Cicchino et al., 2018 [11]	LDW	This study concluded that vehicles with LDW had significantly lower crash rates of all severities (18%), in those with injuries (24%), and those with fatalities (86%). However, the author highlights that the LDW effect is lower when driver demographics were added as a control variable – an 11% reduction in crashes of all severities and a 21% reduction in crashes with injuries.
AAA Foundation, 2018 [12]	FCW, LDW, LKA, AEB, BSM	They estimated that those systems when combined could prevent approximately 40% of all passenger-vehicle crashes, 37% of injuries that occur in crashes, and 29% of all deaths in crashes.
Penmetsa et al., 2019 [13]	LDW	In 2020, 2.7% of single-vehicle lane departure crashes could be avoided in the state of Alabama if 8.5% of the fleet has a lane departure prevention system with 20% effectiveness.
Tan et al. 2020 [14]	LKA	The study predicted a reduction of 14.8% for fatalities and 10.1% for injuries if all vehicles would have LKA implemented.
TomTom, 2021 [15]	ISA	The intelligent speed assistance (ISA), which is a traffic sign recognition-based system, is capable to informs drivers of the current speed limit and automatically reducing a vehicle's speed by limiting engine power – if needed. The system has the potential to reduce accidents by 30% and deaths by 20%.

Besides safety, AD shows the potential to increase the comfort of commuting. Comfort itself depends highly on the subjective evaluation of passengers. Therefore, the first step to comfortable driving is reliable and safe driving automation which will build up trust. Looking into the future, the full automation would allow us to focus on other stuff while commuting which would help to use that time for other activities. Besides the subjective measures, AD can be optimized to drive within the comfort range of objective measures like acceleration, jerks or avoid frequencies that could cause motion sickness. Smooth driving, V2X communication and optimization of a vehicle to operate in an energy-efficient range would reduce traffic congestion and reduce consumption that leads to less pollution. Giving possibility to being picked up by vehicle and not driving yourself allows people that are not able to drive to come to their destination with ease and enables mobility for all. Reducing road accidents, fuel costs, congestion and giving people the ability to be productive while being driven show huge potential savings and improve the economy [16].

The changes that are going to happen and megatrends that are here to stay show benefits regarding sustainability and the environment which are today the biggest concerns we are facing. But it is still a long way to go and those changes will have a huge impact on how we percept our world. The changes go wider than just transport, it will change the way of education, reform jobs, reoriented findings and on the end change our mind-set. This report is only a small part of the way to the future and deals with the literature study of how the road infrastructure and ADAS interact.

This study aims at showing the current advances on ADAS and their interaction with existing infrastructures, particularly traffic signs and road markings which directly impact the Lane-Keeping system and Traffic-Sign recognition. We will present an overview of the state-of-the-art of those systems, the way they work, which type of sensors are currently used and what are the software technics behind them. Despite their progress in the last decade, ADAS systems remain perfectible under certain conditions, we will highlight the limitations with respect to their expected ODD. In the next years, ADAS systems of SAE L0-2 will become a standard on a majority of vehicles and SAE L3-5 will continue progressing, brief overview of market penetration is conducted in this report.

2. AUTOMATED DRIVING BACKGROUND

In the following chapter, the basic terminology of automated driving will be introduced followed by how well is current advances in AD standardized. At the end of this chapter, the methodology behind AD tests and an overview of the remaining challenges will be discussed. Description of the state of the art ADAS for lane support and traffic sign recognition, as well as their limitations and interaction with road markings and signs, are described in the second chapter. Studies on cost estimation and penetration of ADAS on the market is conducted in the third chapter. Finally, the revise on the future trends and specifications are discussed in the fourth chapter.

2.1. Dynamic Driving Task

Dynamic driving task (DDT) considers all the real-time operations and tactical functions, except strategic functions such as trip planning and scheduling.

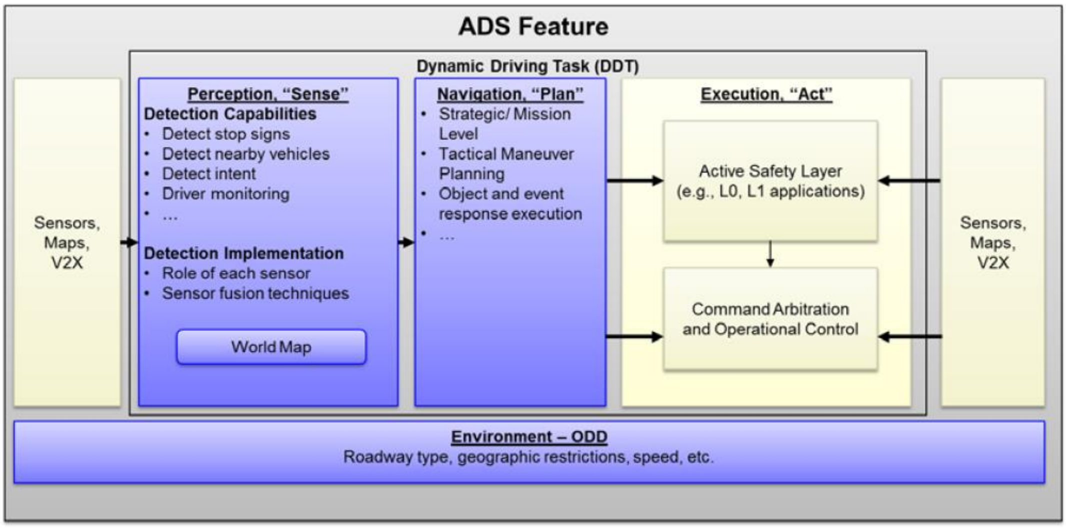


Figure 2 General functional architecture for automated driving system (ADS) (Source: [17])

The simplified form of the functional architecture of the automated driving system (ADS) is shown in Figure 2. The DDT consists of three modules for perception, navigation and execution. Therefore, it can be divided into the following subtasks [18]:

1. Longitudinal vehicle control via acceleration and deceleration.
2. Lateral vehicle control via steering.
3. Object and event detection, recognition, classification, and response preparation and execution.
4. Manoeuvre planning and execution.
5. Providing signals to alert other traffic participants or to enhance conspicuity via lighting, sounding, etc.

2.2. Operational Design Domain

The operational design domain (ODD) [18] is defined as *"operating conditions under which a given driving automation system or feature thereof is specifically designed to* *function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."*

It is used for the verification and validation of ADAS and provides the operating range of AD functionality. The ODD guides the development of test cases either for testing intended functionality or performing hazard and risk analysis. For the higher levels of automation, it is important to detect limits of ODD in real-time to bring the right decision when to activate or deactivate the function, or when to hand out control to the driver.

Content of ODD is grouped in different categories where each category describes what is within and what is outside the operating range. Weather-related condition is one category that defines the operability of vehicles under the rain, fog, show, etc. Other categories are e.g. road infrastructure, which defines the type of the road, road surfaces, lane width, lane markings and much more, under which vehicle should operate. Many more categories are part of ODD and a complete overview can be seen in [17] and [19].

Table 2 Example of the ODD defined for L3 Traffic Jam Drive Feature (Source: [17])

<table>
<tr><th colspan="2">ODD CHECKLIST: L3 Conditional Traffic Jam Drive</th></tr>
<tr><th colspan="2">PHYSICAL INFRASTRUCTURE</th></tr>
<tr><td colspan="2">Roadway Types</td></tr>
<tr><td>Divided highway</td><td>Y</td></tr>
<tr><td>Undivided highway</td><td rowspan="5">N</td></tr>
<tr><td>Arterial</td></tr>
<tr><td>Urban</td></tr>
<tr><td>Rural</td></tr>
<tr><td>Parking (surface lots, structures, private/public)</td></tr>
<tr><td>Managed lanes (HOV, HOT, etc.)</td><td>Y</td></tr>
<tr><td>On-off ramps</td><td rowspan="2">N</td></tr>
<tr><td>Emergency evacuation routes</td></tr>
<tr><td>Intersections</td><td>N</td></tr>
<tr><td colspan="2">Roadway Surfaces</td></tr>
<tr><td>Asphalt</td><td rowspan="2">Y</td></tr>
<tr><td>Concrete</td></tr>
<tr><td colspan="2">Roadway Edges & Markings</td></tr>
<tr><td>Lane markers</td><td>Must be clear</td></tr>
<tr><td>Temporary lane markers</td><td>N</td></tr>
<tr><td>Shoulder (paved or gravel)</td><td>Limited to divided highway</td></tr>
<tr><td>Shoulder (grass)</td><td>Limited to divided highway</td></tr>
<tr><td>Lane barriers</td><td>Barrier, concrete or metal</td></tr>
<tr><td>Rails</td><td>Barrier, concrete or metal</td></tr>
<tr><th colspan="2">OPERATION CONSTRAINTS</th></tr>
<tr><td colspan="2">Speed Limits</td></tr>
<tr><td>Minimum speed limit</td><td>0 mph</td></tr>
<tr><td>Maximum speed limit</td><td><37 mph</td></tr>
<tr><td colspan="2">Traffic Conditions</td></tr>
<tr><td>Traffic density</td><td>Only heavy traffic with preceding vehicle to follow and convoy in adjacent lane</td></tr>
</table>

2.3. SAE Levels of driving automation

The SAE J3016 [18] defined levels of driving automation (Table 3) based on DDT and DDT fallback performance and its allocation between the system and the human driver. Therefore, levels 1 and 2 are known only as support systems as a human driver must supervise the performance of the system and perform part of the DDT itself. Higher levels (3, 4 and 5) are called automated driving systems (ADS) in which systems perform the entire DDT.

Table 3 Levels of Driving Automation (Source: [17])

Level	Name	Narrative Definition	DDT - Sustained lateral and longitudinal vehicle motion control	DDT - OEDR	DDT fallback	ODD
Driver performs part or all of the DDT						
0	**No Driving Automation**	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems.*	*Driver*	*Driver*	*Driver*	*n/a*
1	**Driver Assistance**	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expecation that the *driver* performs the remainder of the *DDT.*	*Driver and System*	*Driver*	*Driver*	*Limited*
2	**Partial Driving Automation**	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* or the *longitudinal vehicle motion control* subtask of the *DDT* with the expecation that the *driver* completes the *OEDR* subtask and supervises the *driving automation system.*	*System*	*Driver*	*Driver*	*Limited*
ADS ("System") performs the entire DDT (while engaged)						
3	**Conditional Driving Automation**	The *sustained* and *ODD-specific* performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user is receptive* to *ADS*-issued *requests to intervene*; as well as to *DDT performance-relevant system failures* in other *vehicle systems,* and will respond appropriately.	*System*	*System*	*Fallback-ready user (becomes the driver during fallback)*	*Limited*
4	**High Driving Automation**	The *sustained* and *ODD-specific* performance by an **ADS** of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene.*	*System*	*System*	*System*	*Limited*

5	**Full Driving Automation**	The *sustained* and unconditional (i.e., not *ODD-specific*) performance by and *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene.*	*System*	*System*	*System*	*Unlimited*

Levels 4 and 5 are capable to control full longitudinal and lateral motion and fall-back functions. In contrary to level 5, level 4 works under limited ODD, which defines circumstances under which a system cannot perform its functionalities. Level 5 is intended to drive everywhere and in all conditions.

2.4. ISAD levels

Similar to SAE levels for driving automation, the ISAD levels are a classification scheme for road infrastructure and its capability to support automated vehicles. Road infrastructure plays a crucial role and can greatly ease the implementation and acceptance of automation driving.

Table 4 ISAD levels (Source: [19])

	Level	**Name**	**Description**	**Digital information provided to AVs**			
				Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Digital infrastructure	**A**	Cooperative driving	Based on the real-time information on vehicles movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow	**X**	**X**	**X**	**X**
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this dana to AVs in real-time	**X**	**X**	**X**	
	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs	**X**	**X**		
Conventional infrastructure	**D**	Static digital information / Map support	Digital map dana is available with static road signs. Map dana colud be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs	**X**			
	E	Conventional infrastructure/ no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs				

The ISAD levels are grouped into conventional and digital infrastructure where level E offers no support for an automated vehicle (AV) and from level C onwards starts the full digitalization of infrastructure. For a better understanding of the ISAD levels, readers are referenced to Table 4 and [20].

2.5. Testing

Before letting AV on the market, extensive tests are needed to guarantee a certain safety level. According to a study by Wachenfeld and Winner [21], the fully autonomous vehicle should drive 6.62 billion test kilometres to prove, with a 50% chance, that AV is twice as good as a human driver. This indicates that testing AV on the real road is neither economically nor justified concerning time costs. Therefore, for testing AV different testing methods exists (Figure 3).

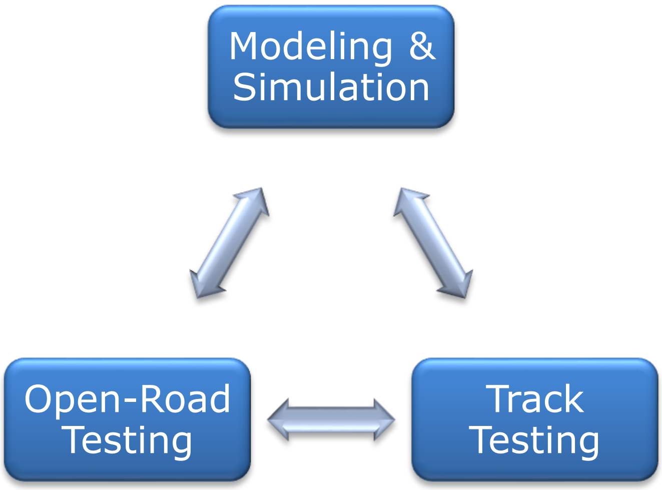


Figure 3 Three common test methods for ADS (Source: [17])

Modelling and simulation rely on virtual models of the environment, vehicles, pedestrians, etc. Therefore, the fidelity of testing depends on the quality of the mathematical models which are often subjects of a trade-off between the quality and cost. This category of testing is not limited to the completely virtual environment. Several sub-techniques exist which are widely used in ADS testing:

- SIL – Software in the loop
- HIL – Hardware in the loop
- VIL – Vehicle in the loop

Track testing technique is somewhere between the testing using the virtual environment and open road. The technique uses real vehicles and mainly real obstacles which provide higher fidelity than virtual testing while still keeping more controllability and repeatability than real road tests. Finally, open-road tests are as real as it gets. This method uses ADS in the public real-world environments which offer the highest fidelity of all testing methods but shows disadvantages regarding costs and safety. Overview of methods advantages and disadvantages is provided in Table 5.

Table 5 Advantages and disadvantages of different test methods for AV

Modelling & Simulation	
Advantages	
Efficiency	Simulation, if do not require very high quality, can be sped up faster than in real-time. With advanced methodology, simulation can be performed only in the relevant range.
Controllability	Many aspects and parameters of the test can be controlled.
Repeatability	Simulation allows us to run tests in the same fashion with the same initial conditions.
Scalability	High numbers of different scenario types can be defined.
Predictability	In simulations, uncertainties are controllable as well, which means they can be performed in a very specified manner.
Disadvantages	
Fidelity	Simulations are only an approximation of reality, therefore, some phenomena cannot be replicated with 100%.
Track Testing	
Advantages	
Fidelity	Track testing often involves real physical and real environmental conditions. In general, offers improved fidelity over the simulations.
Controllability	Track testing still offers a wide range of controllable parameters.
Repeatability	The same tests and initial conditions are in many cases achievable.
Disadvantages	
Cost	Track testing requires a significant amount of time for the setup and execution of test as well as the need for physical systems which increase the cost.
Variability	Despite a wide range of controllable parameters, the variability of those parameters is limited in comparison with the simulation.
Potentially hazardous	As the physical systems and test participants are involved the complete safety cannot be guaranteed.
Open-Road Testing	
Advantages	
Fidelity	The open-road test is the only method that offers complete fidelity.
Disadvantages	
Cost	Real physical ADS, well trained personal and the huge amount of time needed make this testing method rather expensive.
Safety	As ADS drives on the public roads the involves other traffic participants, accidents and traffic participant’s injuries cannot be completely ruled out.
Controllability	Public roads and the real environment makes it, in most cases, uncontrollable.
Repeatability	Events on the public road hardly can be exactly repeated

2.6. Standards for automated vehicles

Standards, guidelines and regulations are a vital part of the lifetime of a product. They cover a huge range of activities from the conceptual phase of product development and managing a process up to delivery and support. Although, it is not often a case that a product must be done according to certain standards or guidelines it is rather the best practice, as those documents are a collection of knowledge of manufactures, researchers, sellers and buyers.

In the domain of ADAS and AV, there is still a lack of uniform understanding and standards. But this is currently a very active field and progress can be seen each year. Already through previous subchapters several standards, guidelines were introduced such as SAE levels of driving automation [18], NHTSA guideline [17] for scenario-based testing or best practice for defining ODD [19]. The full list of available standards applicable for AV can be seen in [22]. The collection of those standards can be divided into several groups. One group are standards that address a particular ADAS feature like ISO 11270:2014 for lane-keeping assistance systems (LKAS) or ISO 20900:2019 for partially automated parking systems (PAPS) and many more. Other groups of standards do not deal with performance requirements and test procedures than rather with harmonizing the formats for describing simulation environments for virtual testing. Examples of such formats are OpenDRIVE, OpenSCENARIO, OpenODD and others provided and maintained by standardization organization ASAM [23]. The third group are a general group of standards, well accepted and widely used, example of such are ISO 26262 for functional safety, ISO/PAS 21448 for the safety of the intended functionality (SOTIF) and UL 4600. Those three are probably the most referenced standards when comes to AV.

ISO 26262 is the international standard for functional safety, intended for electrical and/or electronic systems that are installed in a serial production road vehicle. It differs from the other two that are mentioned here. ISO 26262 deals with the hazards caused by the malfunctioning behaviour of E/E safety-related systems. Based on the risk and hazard analysis and assigned automotive safety integrity levels (ASIL) in the conceptual phase of a product. Standard prescribe the measures to conduct software and hardware requirements, design and test procedures. Important aspects of the safety addressed in the standards are software and hardware design, which on the higher ASIL levels often specify necessary redundancy. In ADAS and AV that would mean having different algorithms or hardware based on the different techniques that serve the same purpose. Currently, ISO 26262 can be applied to the lower levels of driving automation, for higher levels, additional measures are necessary, as in the current standard version risk analysis also depends on a human ability to control function in hazardous situations.

In contrast to ISO 26262, the ISO/PAS 21448 deals with risk and hazards resulting from insufficiencies functionality of foreseeable misuse by a person. This standard provides guidance for verification and validation (V&V) needed for SOTIF, and it is intended for systems of lower levels of automation excluding those for which a well-established V&V process exists. To be fully compatible with higher levels of automation, additional measures are needed.

UL 4600 is built upon ISO 26262 and ISO/PASS 21448. It addresses safety gaps like specifying safety practices for machine learning approaches concerning functionalities for which complete requirements are not available.

2.7. Challenges in higher automation levels

AD is a relatively new field and as such has many challenges that should be overcome to develop safer vehicles. Some of those challenges were addressed in the previous subchapters such as those regarding testing and standardization. This subchapter gives an overview of known challenges. To provide a better understanding they are clustered into three groups (Table 6). One group deals with human interactions, ethics and legal issues. Challenges regarding technology like sensors, road infrastructure, testing and more are part of the second group. Finally, environmental and sustainability challenges are addressed in the third group.

Table 6 Challenges of AD

The human factor, Ethics & Legal issues	
Challenges of partial automation	
Inattention/distraction	Undeniably, ADAS shows potential in accidence prevention, but too much interference of system like a warning, sounds bring discretion in attention [24].
Trust	Over time we gain trust in the system, can come to task inversion, in which humans overtrust the system and let the system perform primary tasks. This can be fatal if a system still has some lack of reliability or is not tested enough for the corner cases.
Drowsiness	Partial automation reduces the need for drivers and increases the percentage of tedious tasks. The study [25] has shown that automation significantly increases tiredness while driving and increase the chance to fall asleep.
Fast reaction	Higher levels of automation where mind drift-off is allowed, humans need some more time to realize the situation again.
Skill-atrophy	if not trained skills are lost, the same goes for driving.
Ethics	
Lack of universal rules	The survey of machine ethics [26], indicates the driver's decisions guided by moral principles vary by culture.
Implications of autonomous vehicles	The implication of AV and artificial intelligence (AI) in general goes beyond moral decisions while driving. AV and AI have big influences on education, jobs, equity of people and many more aspects of everyday life [27].
Legal issues	
Liability	Shifting the responsibility of driving shifts also responsibilities in case of accidents from human drivers to technology. Increases in the use of AV need to be supported with new liability frameworks.
Privacy issues	AD heavily rely on gathering data, which on the other hand could cause privacy issues. In [27] two main risks regarding privacy are highlighted: cyber-attacks and commercial gain of data owners.
Technology	
Sensors	
Sensor fusion	Demands for higher reliability of sensors and handling complex traffic situations require combining and harmonizing multiple sensors.
Range	Currently, camera ranges are up to 80 m and LiDAR up to 180 m, but this is still too less for high-speed scenarios.
Testing	
Corner cases	To cover all possible scenarios when comes to risk assessment, corner cases (rare events) should be properly addressed. Open-road tests are, in general, an inadequate method to test such scenarios. Therefore, the focus is placed on virtual and track tests.
Standardization	AD is a relatively new field and thus suffers from a lack of standards and guidance. However, this is currently a very active topic. Standardization of test procedures and uniforming formats used for the virtual tests will be a major achievement.

Road Infrastructure	
Harmonization	Many AI algorithms use in AD technology rely on learned data like traffic sign shapes, colours, etc. non-harmonized road marking and signs among countries increase complexity in technology design and acceptance.
Maintenance	Machine vision (MV) systems have issues correctly detecting road markings or signs when they are obstructed with dirt, cracks, graffiti or degraded over time.
Design	MV shows worse performance when non-standard road markings or signs are used. Moreover, some of the designs do not show good compliance with MV like yellow markings, electric traffic signs, etc.
Digitalization	Digital maps show huge potential to overcome many issues cause by MV limitations, design and maintenance of road infrastructure.
Environment	
Greenhous gases	
Reduction	Although, reduction of greenhouse gasses is not a direct challenge for AV than rather AV is the solution to it. But still, the path to the point where AV will show environmental benefits is tiled with many challenges. Those challenges are also of social nature as humanity needs to change its mindsets when it comes to mobility. From technical challenges, those are optimization of driving tasks to reduce consumption, create more sustainable processes of vehicle development and many more.

3. OVERVIEW OF THE STATE OF THE ART EXISTING ADAS TECHNOLOGY

This section provides an overview of existing ADAS features used in the domain of lane support and traffic sign recognition. Many commercial names have been used for the same functional feature of ADAS. In this overview, the generic names proposed by American Automobile Association (AAA) [28] are used. Further, the basic principle of perception sensors and lane detection and sign recognition algorithms are briefly described. At the end of this chapter overview of the state of the art of perception sensory and algorithm in interaction with road signs and markings is discussed.

3.1. Advanced Driver Assistance Systems (ADAS)

3.1.1. Lane support systems (LSS)

Lane supporting systems (LSS) is a common name for ADAS features that use lane detection to perform functions such as collision alerts, automated driving tasks or collision mitigation (Table 7). Characteristics and definitions of each ADAS feature that are based on lane detection are given in the following text.

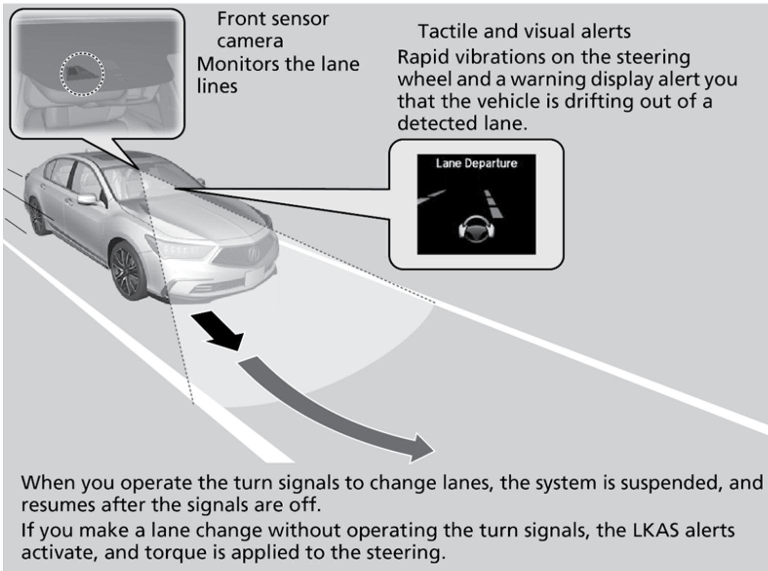


Figure 4 Work principle of LKA (Source: [29])

a) Lane Departure Warning

The Lane departure warning (LDW) is simples among LSS. It alerts the driver through optical, acoustic or haptic feedback when approaching or crossing the lane markings without activation of the direction indicator.

b) Lane Keeping Assistance

The lane-keeping assistance (LKA) is a more advanced version of the LDW and it works on similar principles. Unlike the LDW the LKA prevents a vehicle from departing lane or centring vehicle in a lane by applying a steering toque to correct and control vehicle course. Sometimes the LKA and lane centring assist are considered separately, but in this report and for a purpose of simplicity we will consider it as LKA.

c) Automatic Emergency Steering

Automatic emergency steering (AES) aims to detect a potential collision and automatically mitigate or lessen the severity of impact. The system works on a more complex set of criteria than LKA as its activation criteria consider the assessment of the collision risk. The system is designed with the idea of reducing normal driving interruptions. Therefore, in some cases, if the vehicle crosses the centre marking in absence of the oncoming traffic, the system may not activate an evasive manoeuvre than rather warn a driver.

Table 7 Proposed ADAS terms (Source: [28])

Functionality	ADAS feature	Definition
Collision Alert	Lane Departure Warning	Monitors vehicle's position and alerts driver if the vehicle approaches or crosses lane markings.
Automated Driving Task	Lane Keeping Assistance	Controls steering to maintain the vehicle within the driving lane. It can prevent the vehicle from departing the lane or continuously keep the vehicle in the centre of the lane.
Collision Mitigation	Automatic Emergency Steering	Detects potential collision and perform steering actions to avoid or reduce the severity of impact.

3.1.2. Traffic Sign Detection and Recognition (TSDR)

Traffic Sign Detection and Recognition (TSDR) is an ADAS feature that deals with the recognition of traffic signs in order to automatically adapt the speed when using Adaptive Cruise Control (ACC) or giving additional information to the driver. The information gathered from the Traffic Sign Recognition System (TSRS) could be coupled with information from a digital map with already implemented signs. Even if this system is not new – the Opel Insignia was already able to read signs in 2008 [30] – it still needs to be improved.

TSRS is designed around three main components [31]:

a) Image acquisition thanks to the visual sensor

TSRS are usually based on a forward-facing camera located behind the windshield (Figure 5). Depending on the system, it could be a dedicated camera or the same camera also used for Lane Departure Warning (LDW).

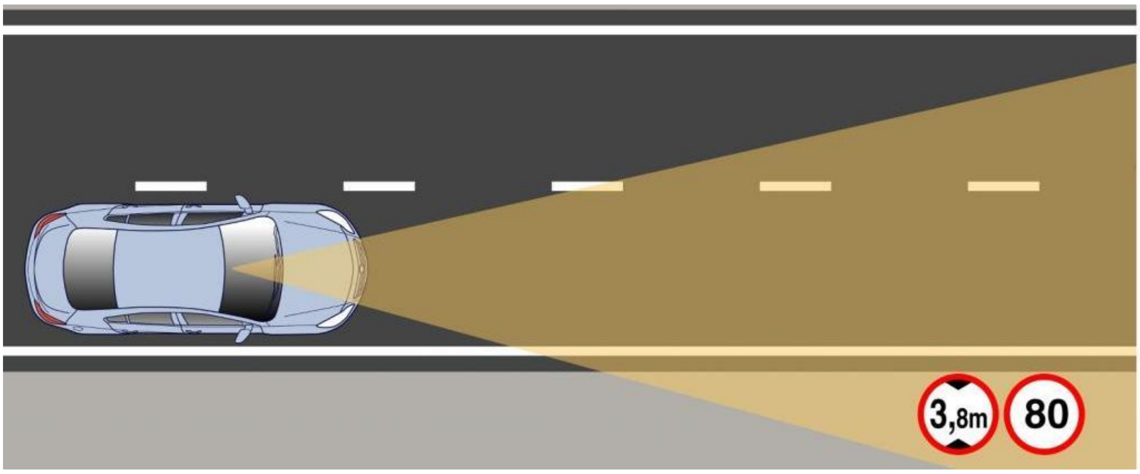


Figure 5 Illustration of how the TSRS works (Source: [32])

b) Image processing

The image processing is divided into two steps, Traffic Sign Detection (TSD), consisting in finding the location, orientation and size of traffic signs and Traffic Sign Recognition (TSR), consisting in recognizing the sign itself and its meaning [30]. The detection itself is commonly done by cameras but LIDAR sensors can also be used, particularly for the TSD as they give more accurate information about the location and orientation of the sign. In order to correctly identify sensors, algorithms based on the analysis of the shape, colours and symbols are used to classify the signs. The literature gives an overview of the limitations of those algorithms and put on the front of the scene some ways to improve them.

c) Vehicle action

Once the sign is recognized, different actions can be performed, information can be given to the driver (Figure 6) and in some cases, the behaviour of the car is automatically adapted. TSRS are commonly used by ACC. In this case, the speed of the car will be automatically adapted depending on the recognized sign.

Figure 6 Speed limit shown on the dashboard (Source: [32])

3.2. Perception modules

Several different sensories are used to perform tasks like LSS or TSR. In the first row, those are perception sensors like cameras, light detection and ranging (LiDAR) and radars, but besides them, global positioning system (GPS) and inertial measurement unit (IMU) sensors are used to estimate vehicle position and motion needed for temporal integration of the frames received by perception sensors. Features for SAE L2 do not require high redundancies and can rely either on camera or LiDAR. But higher automation levels requirements higher reliability. This means that both, hardware and software, need redundancy. Therefore the sensor fusion of multiple sensory will be required. This section explains the basics of functionalities of cameras and LiDAR-s.

3.2.1. Camera

Currently, a camera is the most popular vision system used in ADAS applications which is not odd while is guided by "evolutionary" reasons. Lane markings and traffic signs are designed for human vision and the camera is a technology that can obtain the same visual observation, therefore it is the most suited technology equivalent to human vision. Decades of investment in cameras and machine vision made it the cheapest perception technology on the market. But the cameras are not only popular due to those "evolutionary" reasons. Of all vision technologies, cameras have the highest resolution which provides the highest amount of details of the scenery.

Cameras are optical instruments that pass the light through the aperture to the light-sensitive sensor. Its performance depends on the available light and the ability of the camera (e.g. dynamic range, shutter speed, gain, pixel density, aperture, etc.). Too much or too little light lead to overexposed and underexposed images, respectively, which results in loss of the image information. Cameras used for ADAS (Table 8) are highly sophisticated, characterised with high dynamic range and complex algorithms that enable fast response to abrupt changes in the light conditions. Despite their sophistication, they still suffer from limitations coming from too little or too much light.

Table 8 Camera types used in ADAS and their field of application

Camera type	Description
Mono camera	Used for lane marking, lane edge detection, contour recognition, road sign detection, localization and distance measurement.
Stereo camera	Provide depth/distance measurement for objects detection (like a human eye).
Movable cameras	Used in applications where an increase in the field of view is necessary, like for Park Assist Systems or systems for detection of moving objects.
Infrared cameras	Providing night vision comes with higher costs, but they can detect objects 400m to 500m away.

Images taken with a camera are translated from the 3D real world to the 2D image. This is normally enough to satisfy object detection tasks but not to calculate the distance to objects.

Calculating the distance of objects using stereo mechanisms is an old technique that is based on geometry and disparity and it works also like human eyes. Therefore, methods to calculate depth in images taken with a stereo camera are reliable and stable. On contrary, the mono camera itself does not offer such simple geometrical possibilities and requires more complex algorithms to do that (Table 9). One way to deal with that is to compare object sizes and based on machine learning decide on the distance. This is rather an unreliable method that can fail to estimate correct distance e.g. a kid can be incorrectly recognized as a grown-up person. Another approach is so-called structure-from-motion (SFM) which rely on temporal frames, in the other words, the accuracy of vehicle movement and online calibration. The benefits of the mono cameras are their size and cost, but it has disadvantages in higher algorithm and software complexity, as well as, lower reliability in distance calculation.

Table 9 Comparison between mono camera and stereo camera systems (Source: [33])

Comparison parameter	Mono-camera	Stereo-camera
Image processing requirements	Medium	High
The system is reliable for	Object detection	Object detection and distance-to-object calculation
System cost	1x	1.5x
Software and algorithm complexity	High	Medium

Among all ADAS perception sensors camera offers the most details out of high resolution which makes it an excellent sensor for object detection and recognition task. But the highest challenge is to make those tasks robust in all weather conditions. The biggest problem for cameras is light. Situations where are too many lights like sunset, sunrise or direct light from oncoming traffic cause too bright images and loss of information. On the other hand, too dark environments like night conditions or cloudy weather would cause significant limitations for image quality, solutions can come as more expensive IR cameras. Abrupt changes in lightning conditions like shadows or entrances and exits of tunnels require high-dynamic ranges of cameras.

3.2.2. Light Detection and Ranging (LiDAR)

The original concept of LiDAR was introduced by the Irish physicist Edward Hutchinson Synge in 1930. Since then LiDAR has been used in many applications in geology, geography, archaeology, aircraft industries and many more. With the development of automated driving, LiDAR has imposed himself as a sensory system for perceiving the scenery.

LiDAR works on the Time-of-Flight principle (Figure 7). System Controller emits infrared laser pulses at high frequency which are reflected by the environment and received by photo diodes. Distance from the object and travel time of the pulses that travel with the speed of light are directly proportional. Therefore, the distances from surrounding objects are easily collected using the LiDAR as a sensory for a vehicle.

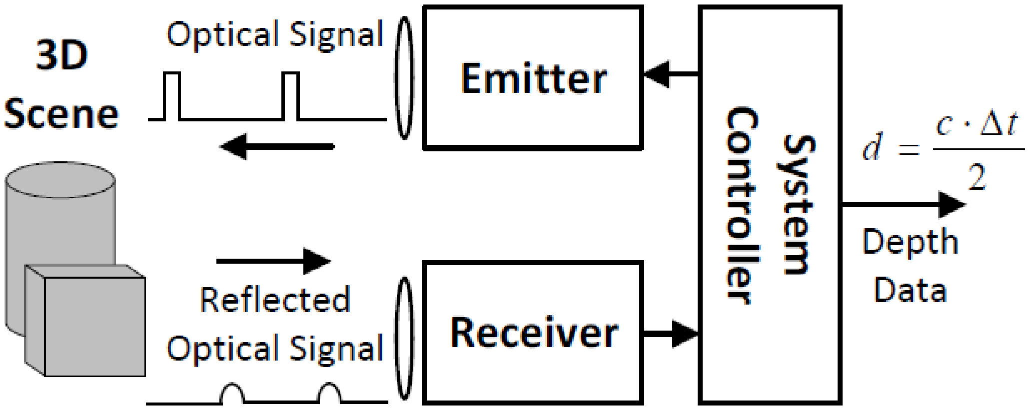


Figure 7 Basic principle of LiDAR (Source: [34])

LiDAR as laser-based systems undergoes safety standards and regulations such as IEC 60825-1 that classify laser products by their factors and regarding potential damage to humans. LiDAR should mitigate potential risks therefore manufacturers aim to achieve Class 1 or Class 1M. Where Class 1 defines an eye-safe system under all conditions, while Class 1M define eye-safety for the naked eye, but not if additional magnifying glasses are used.

The LiDAR outputs point cloud which is a collection of points that can hold information like x,y and z coordinate, intensity, time and many more. Intensity information refers to the reflectivity of the object from which the laser beam bounced and it is recorded as the strength of the returned beam. Intensity can be affected by scan angle, range, surface roughness, surface compound and moisture content [35].

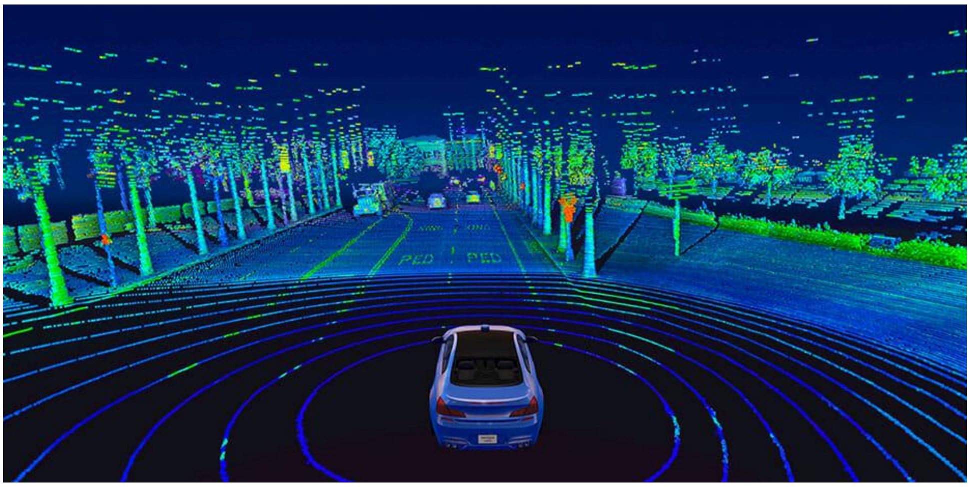
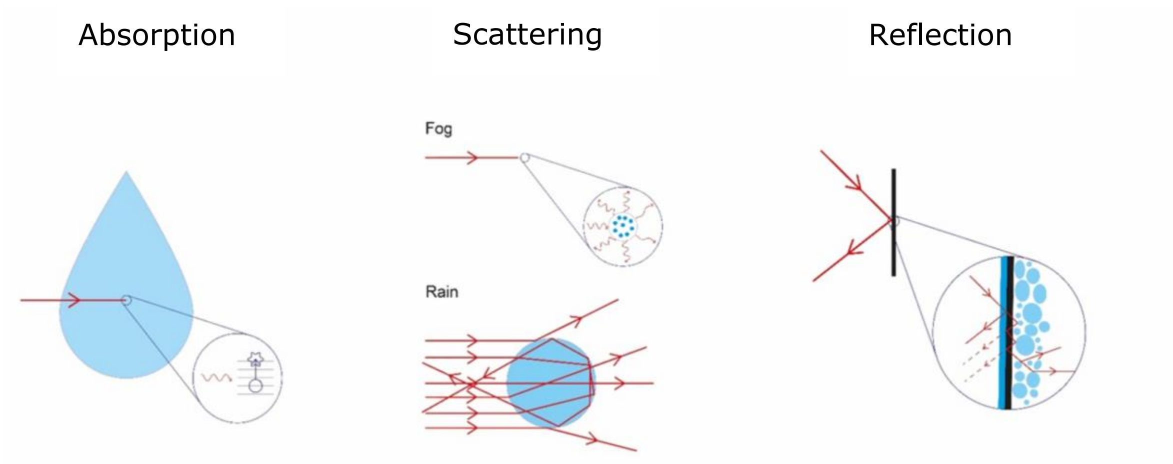


Figure 8 Point Cloud created by Veloydyne Lidar (Source: [36])

LIDAR's comes in different flavours such as mechanical spinning or true solid-state. The mechanical spinning LiDAR is characterised by 360° of the vertical field of view. In contrast, the true solid-state LiDAR has a fixed field of view that works similarly to cameras in that sense. The benefit of having spinning LiDAR is that only one sensor is enough to scan the environment around the host vehicle, although some blind spots due to vertical field of view will be always present. The drawback is that it should be positioned somewhere on the roof of the vehicle to have an unobstructed preview. Another challenge having such LiDAR is keeping it clean all the time. On the other hand, the true solid-state LiDAR can be positioned in places like behind windscreen or integrated into headlights which allows using already available cleaning systems. In contrast to the spinning LiDAR, multiple true solid-state LiDARs would need to be used to cover the same angles as spinning LiDAR.

Figure 9 Mechanical spinning LiDAR from Velodyne [37] and True Solid State LiDAR from Xenomatix [38]

LiDARs benefits are quite clear, they provide a reliable scan of the 3D environment in real-time. Modern LiDAR offers a decent range up to 200 m and a field of view up to 360° in case of spinning LiDAR. But they have certain limitations, like many other sensors, they do not see beyond solid objects, so it must be taken care that LiDARs are unobstructed with the close objects while driving. Another problem comes with adverse weather conditions like rain, fog or snow. According to [39], absorption, scattering and reflection are three mechanisms that have an impact on LiDAR performance under wet conditions (Figure 10). Cost and power usage are other common limiting factors for LiDAR



Absorption occurs due to the interaction of the incident light with the internal structure of material.

For water, significant absorption occurs across the near infrared.

Scattering is the re-distribution of incoming light due to interactions with particles.

For smaller particles such as fog the scatter is strongly wavelength dependent and is caused by electric field interactions.

For larger particles such as rain droplets the scatter is based on internal reflection and refraction. This effect is also responsible for rainbows.

Reflection is the return of light from a boundary with refractive index variation, some of the light will continue past this boundary, interacting further the material.

Surface water acts to change the reflectivity by changing the refractive index of this boundary. Water which enters the pores of a material reduce the reflected signal due to total internal reflections and further absorption and scattering.

Figure 10 Mechanisms that influence LiDAR performance in wet conditions (Source: [39])

3.2.3. Comparison between Camera and LiDAR

Both cameras and LiDAR has their pros and cons, they are not direct competitors than rather devices that will need to work together to enable sufficient redundancy and functional coverage. Direct comparison between camera and LiDAR can be seen in Table 10.

Table 10 Comparison between camera and LiDAR

Parameter	Camera	LiDAR
3D data collection	Distance to objects can be calculated but requires higher effort than LIDAR. +	LIDAR outputs high definition 3D point cloud with distances and intensity. +++
Range	Up to ca. 150 – 180 m	Up to ca. 60 – 80 m
Environment context/details	High-resolution images are very suitable for object detection and recognition. +++	Object detection is possible by recognizing point cloud data patterns. In general, point clouds retrieve fewer details. +
Sensitivity to weather conditions (rain, fog etc.)	Like a human eye, cameras are sensitive to weather conditions like rain, fog, snow etc. -	LIDAR is also sensitive to weather conditions like rain, fog, snow etc. -
Sensitivity on lightning conditions	Cameras are highly dependent on light conditions and show drawbacks in abrupt changes. --	LIDARs in general are resistant to ambient light, except to intensive and direct sunlight. ++
Cost	Cameras are relatively cheap ADAS sensors. ++	LIDARs are rather expensive equipment. --

3.3. Techniques in lane detection

Lane detection methods can be divided into two categories: the traditional and deep learning-based lane detection methods. The traditional image processing techniques have been in recent years slowly replaced by deep learning methods. The review of lane detection is covered in a series of existing survey papers [40], [41], [42] and [43]. This section provides a brief overview of existing methods.

3.3.1. Traditional lane detection methods

The traditional lane detection is characterized by steps presented in Figure 11, namely, image pre-processing, feature extraction, edge and lane modelling and time integration [40].

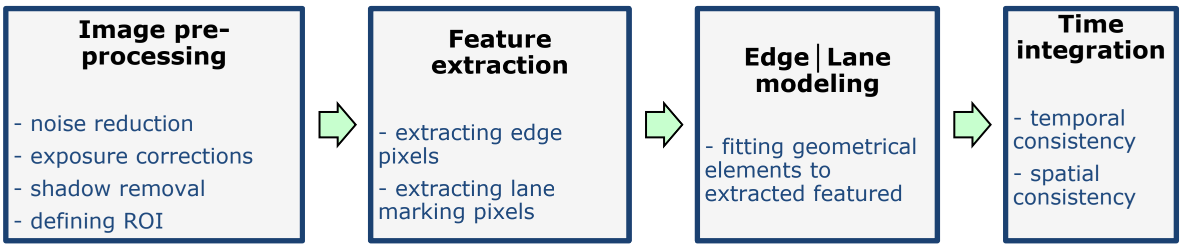


Figure 11 Steps in a traditional lane detection method (Source: [44])

a) Image pre-processing

AIM: In this phase, the aim is to reduce computational time and improve the performance of detection algorithms. This is done by lessening unfavourable illumination effects, noise reduction, enhancement of the image quality and removal of the irrelevant image parts.

METHOD: For noise reduction different digital filtering techniques are used such as mean, median, Gaussian and finite impulse response (FIR) filters [44], [45], [46]. To minimize the effects of the cast shadow and increase the visibility of the lanes, the RGB colour-space is transformed to other spaces like HSV, HSL, LAB, YCbCr [47], [48], [49] and finally converted to grayscale for further support of lane detection. To remove irrelevant image parts and accordingly reduce computational effort for the following phases it is necessary to define the Regions of Interest (ROI). This can be as simple as defining the lower part of an image as ROI and neglecting a sky as an irrelevant part of the image for lane and road detection [50], [51], [52]. Other, more advanced methods [53], [54], require understanding between word, camera and vehicle dynamics. Some of them calculate the depth and reject regions outside desired distance range, while other relays on tracking mechanisms by tracking changes in frames.

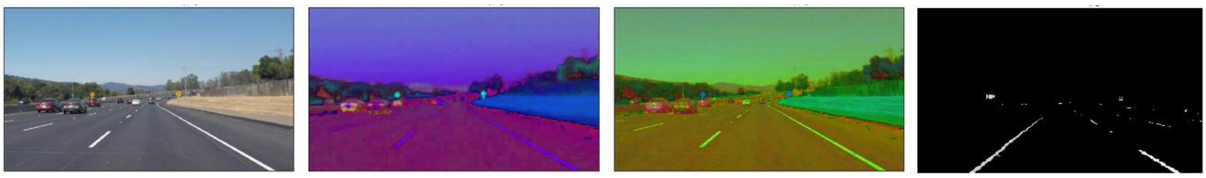


Figure 12 RGB color-space transformation (Source: [55])

b) Feature extraction

AIM: After the image is uncluttered and ROI is defined, a relevant feature can be extracted. This step provides needed information to fit edge and lane models.

METHOD: The simplest approach to lane detection is based on the appearance of shape or colour. Other approaches are applying Sobol, Canny and steerable filters [56], [57]. Often the image perspective is transformed to inverse perspective mapping (IPM) also called "bird's-eye view" to get the histogram that is used to detect the road marking.

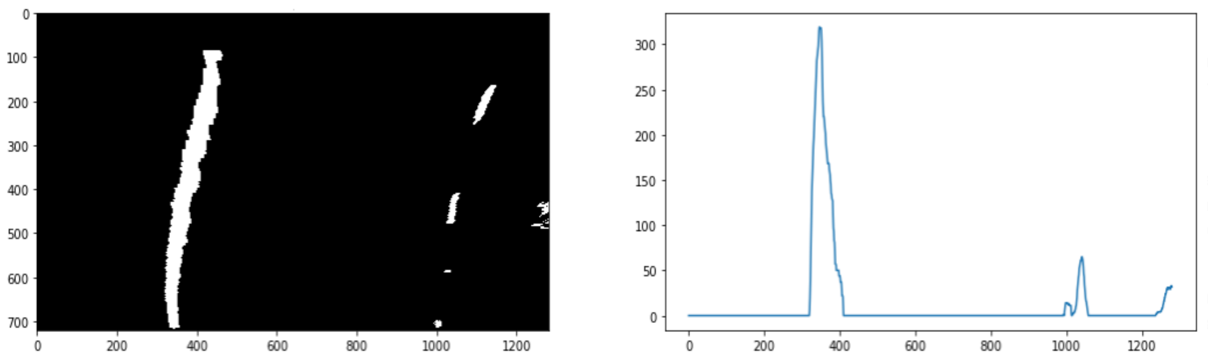


Figure 13 Left: birds-eye view on the lane representation; Right: histogram of pixel intensity (Source: [58])

c) Edge lane modelling

AIM: The points extracted from the road features are used as input data to model the lanes, edges or centreline. The goal of the phase is to create the paths that the vehicle should follow.

METHOD: This modelling is done by fitting the geometric elements to the extracted features. The popular method is to use Hough transform. The models can be divided into parametric, semi-parametric and non-parametric [40].

Figure 14 Lane marking modelling (Source: [55])

d) Time Integration

AIM: This phase aims to achieve temporal and positional consistency by integrating frames using lane tracking [59], [60], [61], [62].

METHOD: For the lane tracking algorithms, Kalman filters and particle filters are widely used, due to their ability to predict objects future location. The estimation of vehicle dynamics is used and integrated with the geometrical models to predict previously detected lanes in the current frame. Vehicle motion can be captured with the ego-motion model, car odometry or combining GPU and IMU.

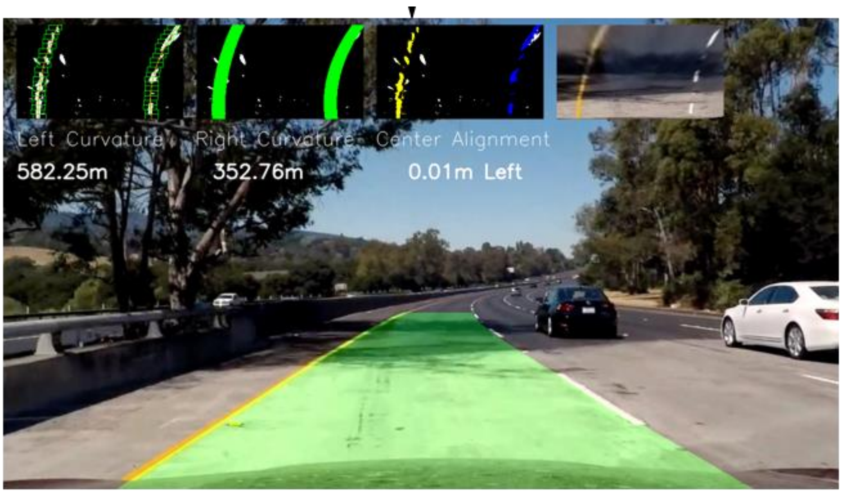


Figure 15 Lane detection (Source: [58])

3.3.2. Deep learning detection method

Deep learning lane detection methods are more promising and replace traditional methods. The huge benefit is that they are learnable, unlike the traditional methods that depend on the camera and set of conditions. In deep learning, the most commonly used algorithm for visual imagery is the convolutional neural network (CNN), which is also applied in lane detection tasks.

a) Data Collection

Learning algorithms largely depend on the quality of the training data. Ideally, training data, are collected during driving in different conditions such as day, night, rain, sunrise, sunset, etc. Data collection together with the labelling process is the most expensive and time-consuming part of the deep learning process.

b) Labels

Labelling is a process of adding meaningful and informative labels to the raw images, they represent ground truth and are used for the training set. In the object detection tasks, labels can be assigned only to the lanes, in that case, we are talking about the so-called single-task model. In other cases when labels are also assigned to objects like signs, vehicles, pedestrians, we deal with a multi-task model (Figure 16). For lane detection, different labelling methods are introduced like masking the ego lane or manually adding meta data defining rectangles around objects and manually fitting polynomials over the lane markings on the raw images by predicting polynomial coefficients. The promising method, in detection, is semantic segmentation in which each pixel is labelled [63], [64], [65].

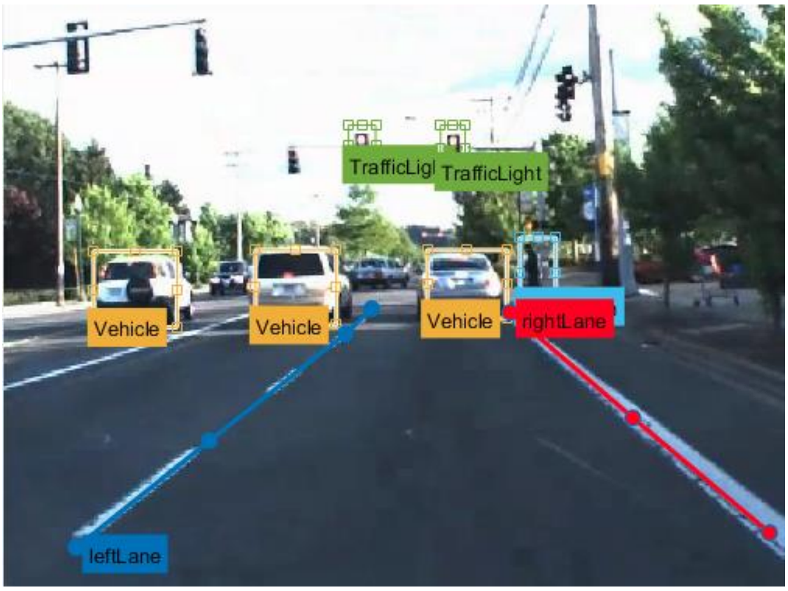


Figure 16 Image labelling (Source: [66])

c) Learning

In semantic segmentation, learning is done through the layers of the convolution where each layer is dedicated to a certain channel e.g. different edges or lanes can be considered as different channels. Adding temporal integration, downsampling and upsampling, algorithms become more efficient and reliable [65].

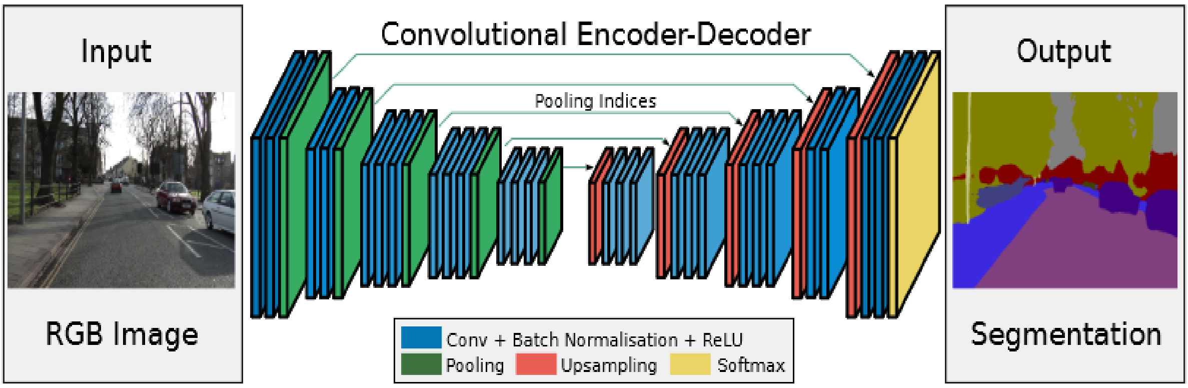


Figure 17 Illustration of segmentation process using CNN (Source: [65])

3.4. Techniques in traffic sign recognition

To be easily understood by drivers, traffic signs are easily recognizable thanks to high contrasting colours combined with specific shapes. The combination of those two features represents traffic-sign categories: danger, prohibition, indication, obligations. TSRS also apply those features to classifiers and classification algorithms such as support vector machine, random forest, neural network, convolutional neural network (CNN), decision fusion and reasoning [67].

The first step when dealing with TSRS is TSD. TSD can use 3 different methods:

a) Colour-based methods

b) Shape-based methods

c) Hybrid methods

a) Colour-based Methods

Those methods take advantage of the fact that traffic signs are easily recognizable and distinguishable thanks to contrasting colours.

Colour-based methods (Figure 18) use the RGB (red, blue, green) colour space, the HIS (hue, saturation, intensity) colour and the HSV (hue, saturation, value) colour space and several other colour spaces in order to reason on the features of the image and recognize the sign.

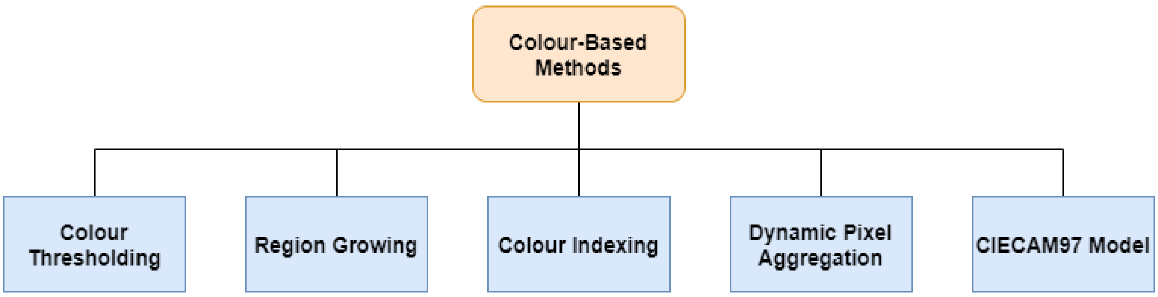


Figure 18 Colour-based methods (Source: [68])

b) Shape-based Methods

Shape-based methods don't lie at all on the colour component of road signs and only consider the shape. As the colours of traffic signs change according to illumination, shape-based methods are preferred for traffic signs recognition.

Even if those technics are efficient, they require high computational and memory. Moreover, they are influenced by the state of traffic signs, partially obscured, damaged or blurred traffic signs may cause difficulties to recognize.

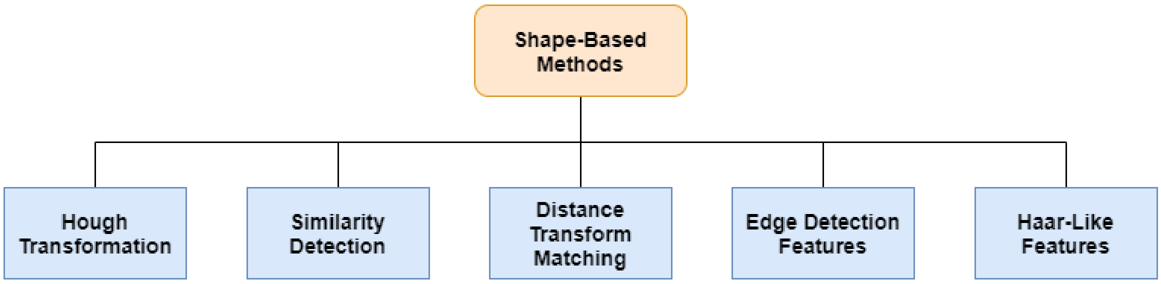


Figure 19 Shape-based methods (Source: [68])

c) Hybrid methods

To get rid of both limitations from colour-based methods or shape-based methods, those technics take shape-based methods as a basis with additional colour aspects or take the colour as a basis plus some shape features. Hybrid methods have been tested for study purposes but are not currently used on the market.

Table 11 Comparison of different methods

Criteria	Colour-Based method	Shape-Based method	Hybrid methods
Low computing	+++	---	++
Computation speed	++	+++	+++
Robustness	++	--	++
Low sensitivity to other factors (lightness, distance, sign conditions)	---	---	--
Use of grayscale images	N/A	+++	++
Accuracy	++	++	+++

3.5. Limitations

Machine vision highly depends on contrast which can be defined as the ratio of the luminance of bright and dark areas of an image. This means if the images are subjects to light variation, different weather conditions, contrast appearance differs and visibility of the lane markings and signs can be insufficient for LSS and TSRS. Visibility is expressed with the coefficient of retroreflected luminance (R_L) and the luminance coefficient under diffuse illumination (Qd) for night and daytime, respectively [69].

Aggravating factors are not limited to light variation or weather conditions only, which are more related to the limitations of the camera itself. Design patterns or inappropriate maintenance can also cause issues in detection and recognition. Table 12 and Table 13 show a list of aggravating factors that can cause issues for lane detection.

3.5.1. Performance of LSS under different conditions

When the visibility of the lane markings is held at good conditions above 100 mcd/lx/m^2 or preferably around 150 mcd/lx/m^2 [70], and when weather conditions are favourable (dry, light rain), the lane is detected with a high confidence rate [71]. However, the confidence rate significantly drops under rainy conditions during the night, especially with the glare source [72] (see Figure 20). To answer the questions what is the minimum requirements at nighttime under wet conditions, many studies conducted such investigations and concluded that R_L should be kept between 20 – 50 mcd/lx/m^2 ([70], [73], [74]). In general, it is observed positive correlation between detection confidence and R_L ([71], [72], [74]).

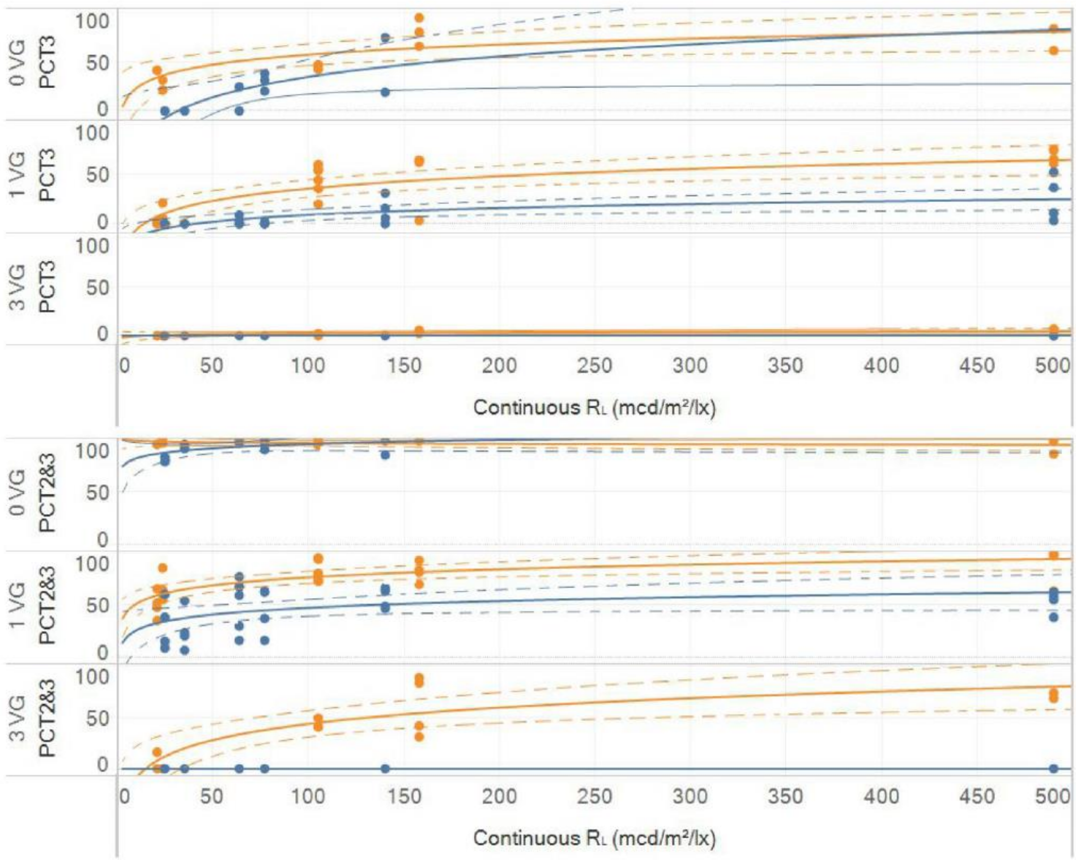


Figure 20 Confidence ratings depending on the different night-time levels (Source: [72])

Figure 20 Plots shows high confidence rating (PCT3) and moderate-to-high confidence rating (PTC2&3) in comparison with R_L; with (1VG and 3VG) and without (0VG) glare source; the blue line represents left lane marking adjacent to the glare traffic, while orange line is the right lane.

To increase the visibility of the night and rainy conditions, several technologies could be proposed. The use of large-size retroreflection materials (glass beads), profiled markings that have raised profiles with retroreflective materials along the vertical walls to reduce flooding and promote water drainage, and the use of all-weather marking paints and tapes that uses special optics to give a high level of dry and wet reflective performance ([73], [75]).

Road marking design parameters like marking width, colour or pattern (solid, dashed, etc.) influence marking detection. Several studies investigated how an increase in lane marking width from 100 mm to 150 mm influence the detection rate, it is concluded a positive correlation between the confidence of detection and wider lane marking ([69], [69]). Regarding colour, yellow marking shows worse behaviour than white ([72], [74], [76]). Regarding pattern, solid lines show the best performance [76].

A literature overview regarding road marking specifications and performance under different weather conditions, and parameters are given in Table 12.

Table 12 Aggravating factor in lane detection

Environmental conditions
• Adverse weather conditions such as rain or snow • Lighting conditions (daytime/night-time or backlight)
Lane maintenance
• Visibility of road markings (e.g. faded) • Multiple lane markings such as at construction sites or residuals of old markings • Road surface with debris, potholes or cracks that could be misinterpreted by the lane detection system
Lane markings appearance
• Coloured road markings (yellow) lower the contrast ratio between marking and pavement • Lane markings not in normal use • Discontinuous markings (e.g. intersection)

Examples of challenging situations for LSS are shown in Figure 21.

a) Limitation for lane detection shown on greyscale images

b) Example of seal joint that could confuse MV

c) Example of obscure intersection and exit ramp

Figure 21. Examples of problematic situations for LSS (Source: [77], [78])

Table 13 Overview of literature findings – lane detection

Factor	Findings
Rain	• Under 30 mm/h rainfall, for a vehicle between 48 and 60km/h, the view range converged to 0 and the ADAS can't operate. The system can operate until 20mm rainfall. [79]
Day/Dry	• High-efficiency rate under dry or light rain conditions with retroreflectivity of marking between [71]
Night/Dry	• Minimum recommendation for R_L = 150 mcd/lx/m^2 [70] • Retroreflectivity contrast ratio with at least 3:1, preferable 5:1 have adequate detection confidence ([76], [78])
Night/Wet	• Efficiency between 0 - 30% - positive correlation with the increase of retroreflectivity of road markings [71]
Fog	• Foggy conditions are much more an issue than rain. Under Fog conditions, the contrast ratio is quite low and the system can't operate well. [75]
Road marking width	• 150 mm road marking are easier to detect than 100 mm ([69], [74])
Road marking colour	• White colour is preferable over yellow ([72], [74], [76])

3.5.2. Performance of TSRS under different conditions

Besides issues caused by camera limitation like variable lightning conditions or weather conditions, factors like damage, location or installation play an important role. Study [80] has shown that even minor changes on signs due to graffiti or damages have a significant influence on TSRS reliability. Placing signs not according to standards or when multiple signs are close to each other often lead to recognizing the wrong sign. Similar is with speed limit stickers that can be found on busses, vans and trucks, they can potentially be misinterpreted by the system and used as a reference for the speed limit. Some other TSRS challenges are shown in Table 14, while the literature overview is given in Table 15.

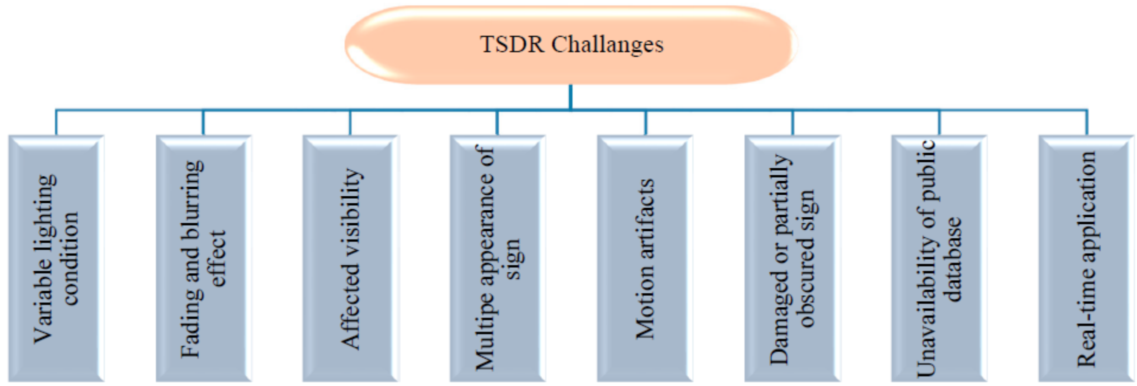


Figure 22 TSRS Challenges (Source : [81])

Table 14 Aggravating factor in traffic sign recognition

Installation and maintenance
• signs not placed according to standards • fading, damage, graffiti, etc. • signs not installed by traffic authorities: signs printed on rubbish bins, heavy vehicles • roadworks signs • TSRS systems recognise any valid number within the annulus as a speed limit sign
Positioning and collocation
• Collocated traffic signs that apply to different motorists • Roadwork and temporary signage • TSRS systems cannot currently interpret text qualifications
Design
• Time-dependent speed zones • Weather-based speed signs • TSRS systems cannot currently interpret text qualifications
Electric signs

- Flickering in the VSLS display
- Multiple collocated signage and distinguish which sign may apply at a given time or under a given condition
- The similarity in shape between the numerals (e.g. 30 km/h, 60 km/h and 80 km/h)
- Variable speed limits are not consistently read
- Collocation with static speed signs

Table 15 Overview of literature findings – traffic sign recognition

Conditions	Findings
Day/Dry	• Variable lighting conditions even in the day affects the performance of TSRS. [81]
Wet/Fog	• Vision-based systems are not able to recognize signs under heavy rain or thick fog. [82]
Poor maintenance	• The reflectivity conditions are far more significant than weather variations. The low reflectivity from "engineering grade" signs causes more difficulties to TSRS. [83] • Graphical changes on traffic signs cause difficulties to TSRS. Different scenarios were tested to evaluate performances. [80]

4. MARKET PENETRATION TODAY AND IN FUTURE

4.1. Mandatory ADAS

In European Union, a new regulation (Regulation (UE) 2019/2144) taking effect on July 6, 2022 will make some ADAS features mandatory for new vehicles. These systems aim to improve the safety of the passengers and also the other road users, more particularly Vulnerable Road Users (VRU).

Table 16 lists the mandatory ADAS features by 2022 depending on categories of vehicles.

Table 16 List of mandatory ADAS features by 2022

ADAS feature	Cars	Vans	Buses	Trucks
Advanced emergency braking	X	X		
Intelligent speed assistance	X	X	X	X
Lane-keeping assist	X	X		

Intelligent speed assistance is impacted by the efficiency of TSRS. As this feature will be mandatory, the TSRS need to be robust enough to improve safety at all time. As of today, TSRS face a lot of difficulties due to the state of the road marking or their positioning (ex: speed limit on a truck, speed limit for highway ramp too close to the main road, etc.).

At the end of 2020, only 10% of the billion cars in use all over the world are equipped with ADAS features ([84]).

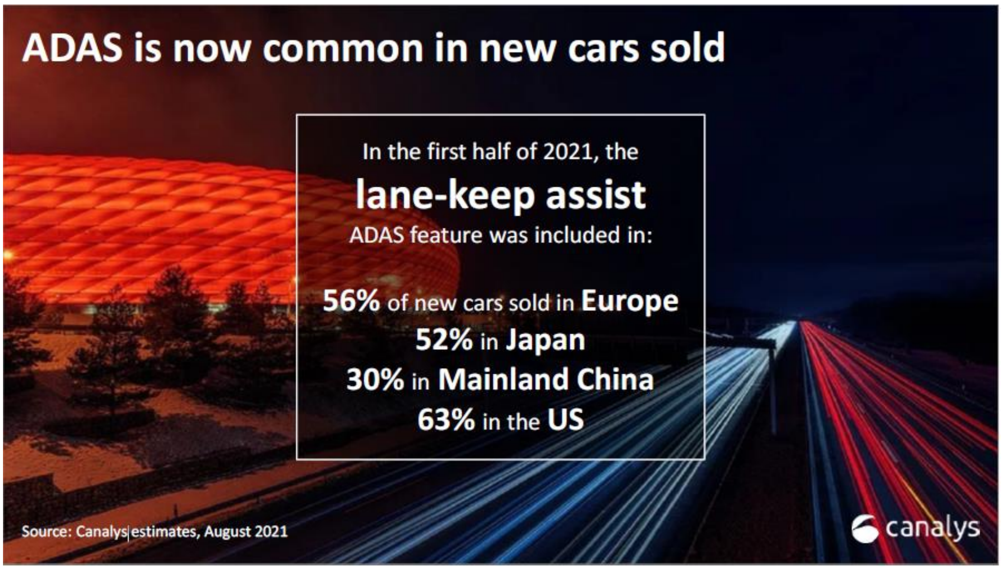


Figure 23 Overview of LKA market penetration (Source: [84])

In August 2021, 56% of new vehicles in Europe were equipped with LKA, one of the mandatory ADAS in 2022. Moreover, only 19% of new vehicles were equipped with Level 2 ADAS at the end of 2020 in Europe [85].

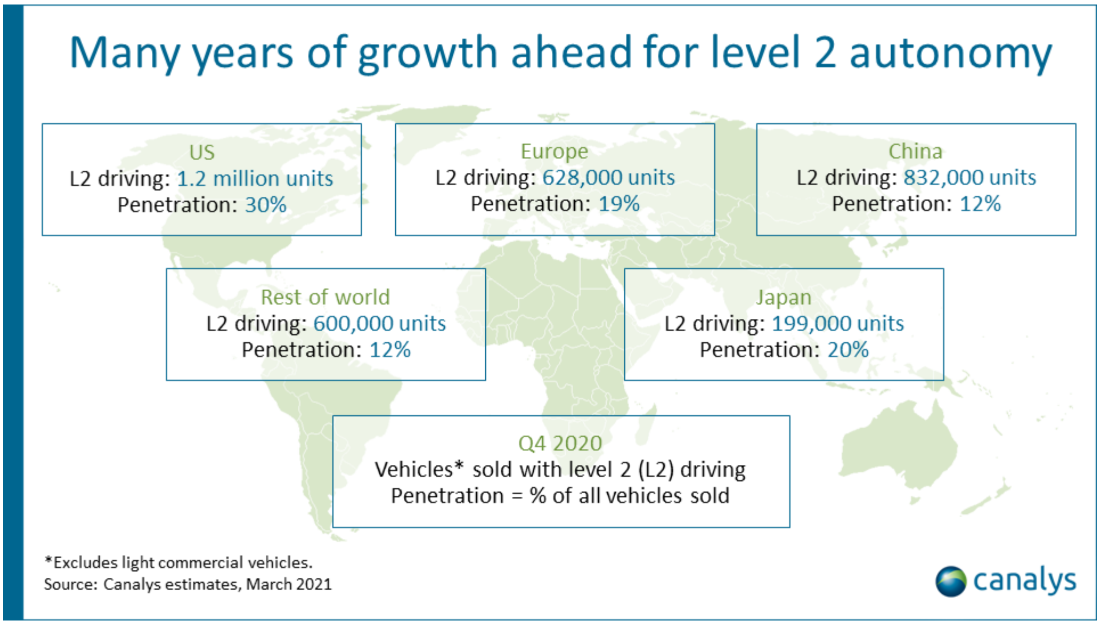


Figure 24 Market penetration of Level 2 ADAS in 2020 (Source: [85])

In the EU, as the main part of vehicles are more than 10 years old, it will take at least 10 years before most of the fleet is equipped with the mentioned ADAS [86]. In order to speed up the penetration of ADAS in the EU, we could envisage retrofitting existing cars. In early 2020, The European Commission published a report on the costs and benefits of retrofitting ADAS [86]. Retrofit systems to be considered are FCW(Forwarded Collision Warning) related to Advanced Emergency Braking, SLI (Speed Limit Information) related to Intelligent speed adaptation, LDW(Lane Departure Warning) related to LKA.

The installation of a complete retrofit bundle (FCW, LDW and SLI) is estimated at 900€ (700€ of equipment + 200€ of installation time) [86]. Considering the price which is not so high, retrofitting can be considered as a serious option to speed up ADAS penetration.

As a comparison, the impact on the price of new vehicles is estimated at 500€ for cars and vans and about 1000€ for buses and trucks. [87]

4.2. ADAS market penetration in the next years

Recently, Japan become the first country to let SAE L3 vehicles on the market – in November 2020, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) granted Honda approval for a Level 3 autonomous driving system. The successful certification of Honda's Traffic Jam Pilot automated driving technology allows autonomous driving with production vehicles on Japanese public highways at speeds up to 50 km/h [88]. Honda is not only an early bird in adapting the L3 automation level. In 2019, Audi announce a Level 3 traffic jam pilot with its A8 flagship sedan, but they never received regulatory approval for the system in Germany. Other carmakers also hold the technology for higher automation levels shelved and wait for regulatory organizations to give the green light. An indicator that there is a huge motion on the regulatory domain is news that German lawmakers have approved a new law with intends to bring SAE Level 4 automated driving into operation in 2022 [89].

Roland Berger, the management consultant, made a study in the spring of 2021 forecasting ADAS market penetration by 2025 [90]. Over 80 tier 1 manufacturers, automotive suppliers, and industry experts, as well as, 3000 drivers to estimate demand for ADAS were interviewed. The study considered Europe, USA and China. They concluded the following:

- By 2025, 85% of vehicles produced globally will have the level of automation L1 and above. While penetration of L4 or L5 features will not be more than 1%.
- By 2025, L3 and higher features will account for no more than 10-15% of total ADAS penetration, whereas L2 features will achieve over 30% penetration across all regions.
- Due to stricter regulations, Europe is expected to have the greatest penetration of new ADAS vehicles sold by 2025.
- By 2025, on a global scale, it is expected 14% of the world's vehicles to have no ADAS features, 40% with L1 features, 36% with L2 features, and 10% with L3 or higher features.

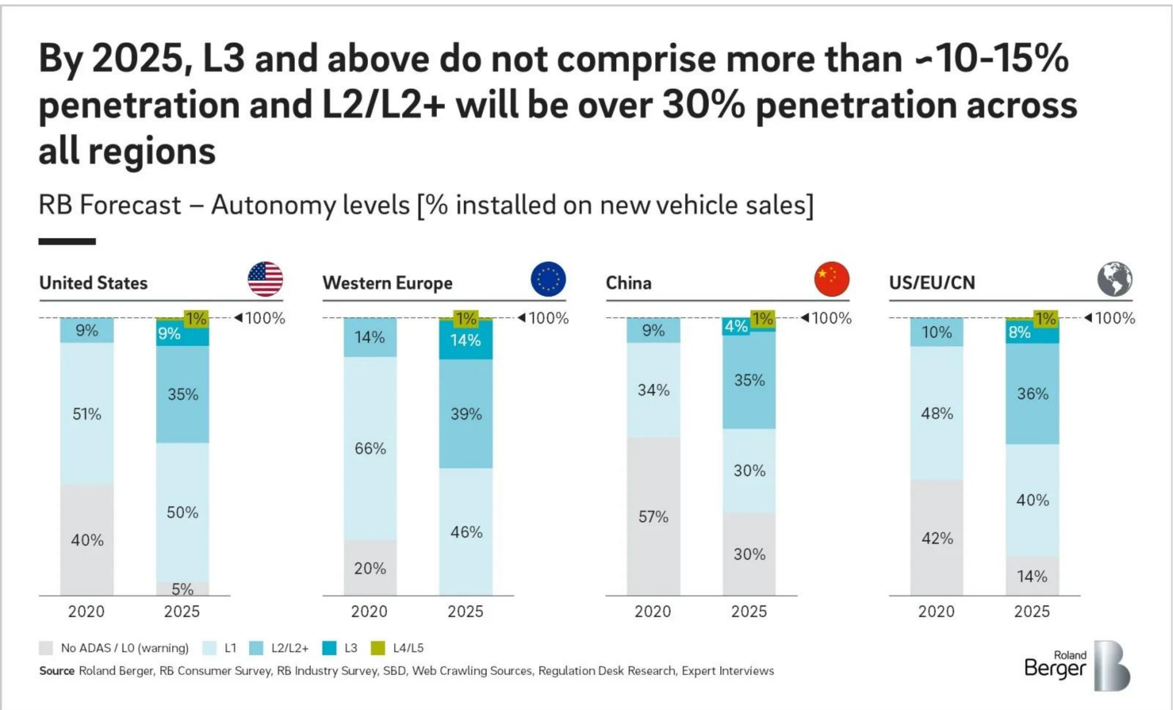


Figure 25 Estimates of penetration of AD by 2025 (Source: [90])

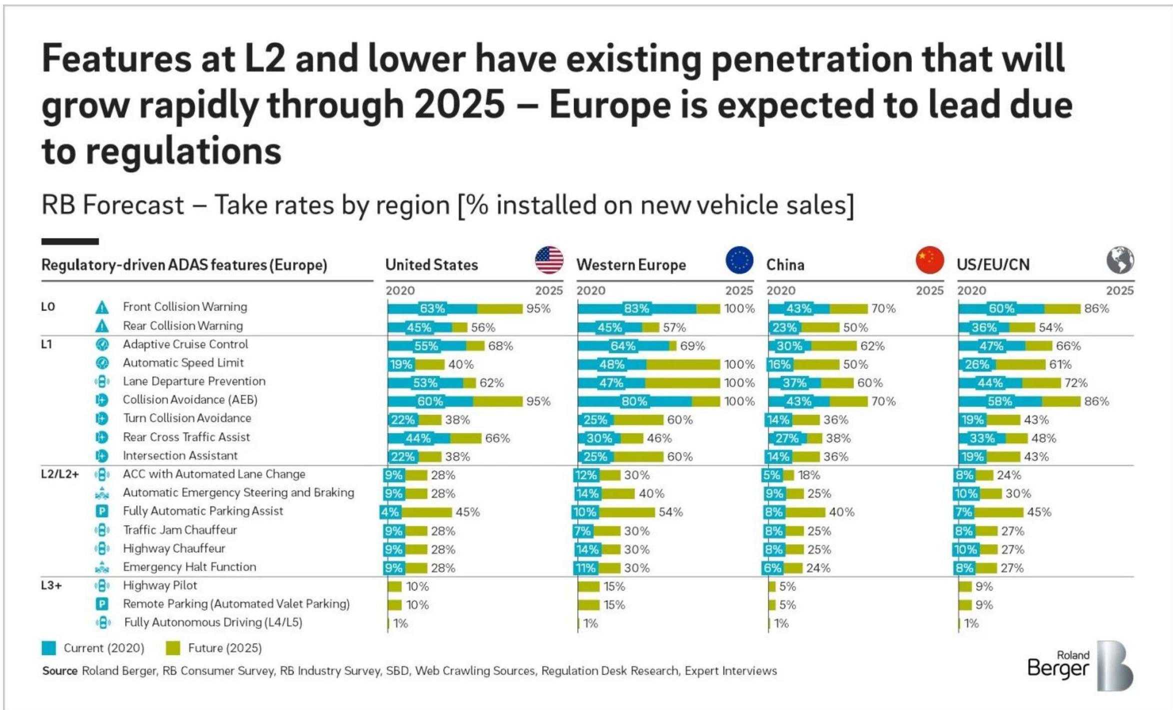


Figure 26 Estimates of ADAS feature penetrations by 2025 (Source: [90])

5. A SUMMARY OF THE SPECIFICATION OF SENSOR TECHNOLOGY

5.1. Sensor fusion

The key component of self-driving cars is the sensors. Sensors are used to collect data that is analyzed by the computer in the vehicle and used to control the motion of a vehicle. The sensor can be categorized into two classes. The first is for internal measurements of dynamic systems (GPS, accelerometers, gyroscopes, gyrometers) and the second for external measurement, surrounding system (cameras, lidar, radar, sonar).

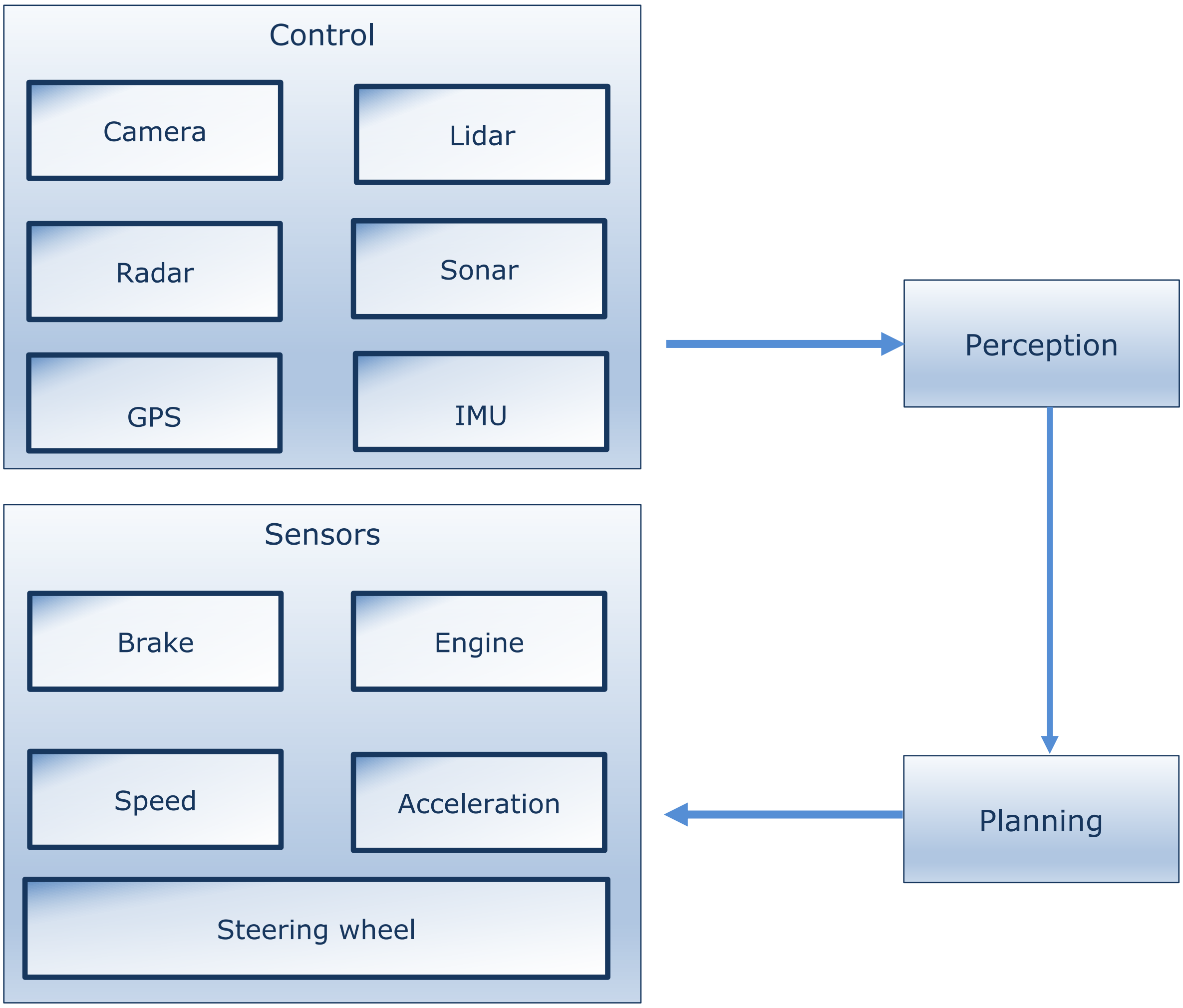


Figure 27 Block diagram of AV (Source: [91])

In general, It is difficult to gather data from a single sensor and use it in the decision-making of complex systems. The reasons can be sensor errors, the nature of the environment, or both. To avoid such problems some high accuracy sensors exist, such as Differential Global Positioning System, Real-Time Kinematic Positioning sensor, etc. However, they are expensive and can be impractical for use in seld driving cars due to operating limits.

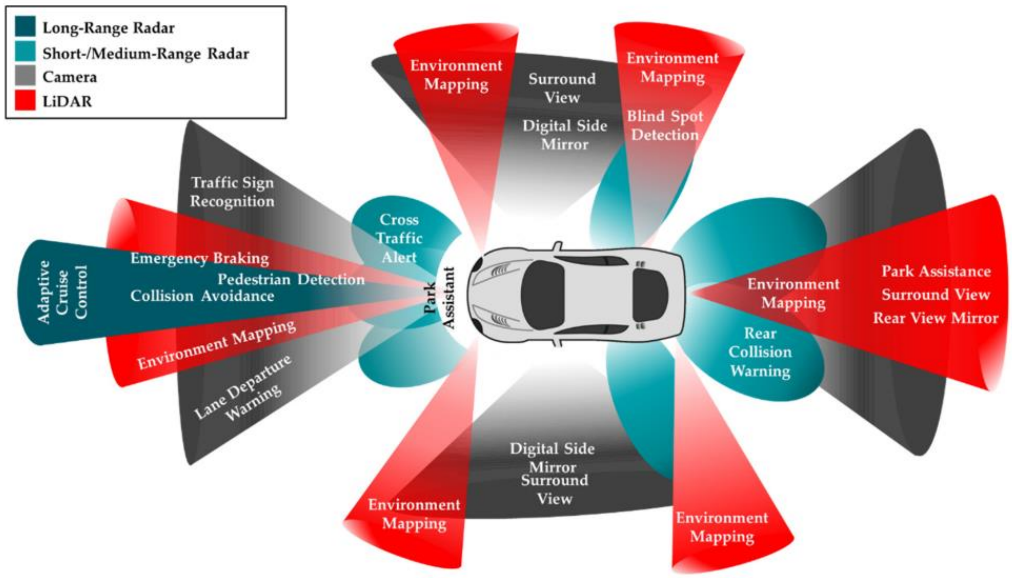


Figure 28 Type of sensors and features for the vehicle perception (Source: [92])

The other solution is Sensor Fusion which is to use different combinations of sensors and fuse their data at different levels to compensate for the limitation of individual sensors. The resulting information is more certain than it would be possible when these sources were used individually. This is especially important when different kinds of information are combined. For example, on the autonomous vehicle, it is important to have a camera to clone a human vision, but the information of the obstacle distance will be best gained through the sensors as lidar or radar. For that reason, sensor fusion of camera with lidar or radar data is very important since there are complementary. On the other hand, combining information from lidar and radar will provide more certain information about the distance of the obstacle ahead of the vehicle or the general distance of the objects in the environment. [91]

Table 17 Limitations of sensors and advantages of sensor fusion in AV applications (Source: [93])

AV Application	Fused Sensors	Limitations without Fusion	Fusion Advantages
Pedestrian Detection	Vision and LiDAR	Sensitive to illumination quality; Night vision difficulties by vision camera only. The low resolution of LiDAR 3D Scene reconstruction when used alone.	Ability to measure depth and range, with less computational power; Improvements in extreme weather conditions (fog and rain)
Pedestrian Detection	Vision and Infrared	Night vision difficulties with vision camera only; Thermal cameras lose fine details of objects due to their limited resolution.	Robustness to lighting effects and nighttime detection; Infrared camera provides distinct silhouettes of objects; Ability to operate in bad weather conditions.

Road Detection	Vision and LiDAR	Illumination and lighting conditions; High computational cost for vision depth measurements; Limited resolution and range measurements by LiDAR; Sparse and unorganized point cloud LiDAR data.	Road scene geometry measurements (depth) while maintaining rich colour information; Calibration of scattered LiDAR point cloud with the image.
Road Detection	Vision and Polarization camera	Sensitive to lighting conditions; Lack of colour information.	Polarized images enhance scene understanding, especially with reflective surfaces.
Vehicle Detection Lane Detection	Vision and Radar	The low resolution of the radar. The camera needs special lenses, arrangements, and heavy computation to measure distance.	Measure distance accurately; Performs well in bad weather conditions; Camera is well suited for lane detection applications.
Visual Odometry	2D Laser scanner and Vision	2D scanners can miss detection of objects in complex environments; 2D images are insu_cient for capturing all the features of the 3D world.	Fusion of vision and 2D scanners can replace the need for 3D LiDAR, and hence reduce price and computation load.
SLAM	Vision and Inertial Measurement Unit	Illumination and lighting conditions by the camera; Camera suffers blur due to fast movement; Drifting error for IMU.	Improved accuracy with less computational load; Robustness against vision noise, and corrective for IMU drifts.
Navigation	GPS and INS	GPS outage in denied and canyon areas; Drift in INS readings.	Continuous navigation; Correction in INS readings.
Ego Positioning	Map, vision, GPS, INS	GPS outage; INS drifts; HD map accuracy; Visibility of road markings.	Accurate lateral positioning through road marking detection and HD map matching.

5.1.1. Trends in Sensor Fusion

At present, three primary combinations of sensors are used for perceiving the environment, which is Radar-Camera, Camera-Lidar, and Radar-Camera-Lidar. The results show that Radar-Camera is the most widely used sensor combination as this combination can achieve excellent resolution while obtaining distance information from surrounding objects. Image depth information can also be obtained from the combination of LiDAR and camera. Some studies combine LiDAR and Millimeter-Wave Radar with cameras to improve security redundancy. Both radar and camera are complete and inexpensive technology [94].

5.1.2. Challenges in Sensor Fusion

Undoubtedly, the multi-sensor fusion technologies, primarily based totally on enormous research, have executed incredibly complete blessings in self-reliant systems. Sensors equipped with this system could generate a large amount of data per hour. Hence, it requires high computational power to process data. It is a challenge to train and record data for all possible scenarios, including but not limited to the location, terrain, and weather that an autonomous vehicle may encounter in the real world. Other sensor fusion challenges include biases in collected datasets, overfitting of training datasets, imprecision, and uncertainty in the data measurements, such as noise relating to calibration errors, quantization errors, loss of precisions, missing values, et cetera. Transforming multi-sensor data into a standard frame of reference may also pose a challenge in sensor fusion implementations. From an environmental perspective, one of the remaining challenges of sensor fusion for reliable and safe perception is the performance of vision sensors in harsh weather conditions such as snow, fog, sandstorms, or rainstorm. Such conditions can impact the vision and range measurements of vision sensors, leading to a decrease in visibility distance and resulting in erroneous and misleading outputs [92].

5.2. Connectivity

Currently, AVs and vehicles equipped with ADAS depend solely on their sensors to perform perception tasks. This has many limitations, one of which is unreliable detection and recognition systems which is important to reduce the response time of vehicle actions triggered by events such as braking of the vehicle in front. Coverage of blind spots, adjusting steering, acceleration and deceleration depending on the upcoming road, limited perception distance, accurate localization, are all limitations that could be addressed with V2X connectivity. Connectivity can bring so needed redundancy and enhance safety and driving comfort. Improving infrastructure and upgrading with the possibility of cloud calculation of vehicle trajectories or locations has the potential to reduce requirements for sensors. Proper communication in V2X plays a crucial role in managing scenarios like intersections, highway ramps, parking or other complex urban environments.

Connectivity addresses the problem with insufficient information in road traffic and offers a solution to sensor limitations.

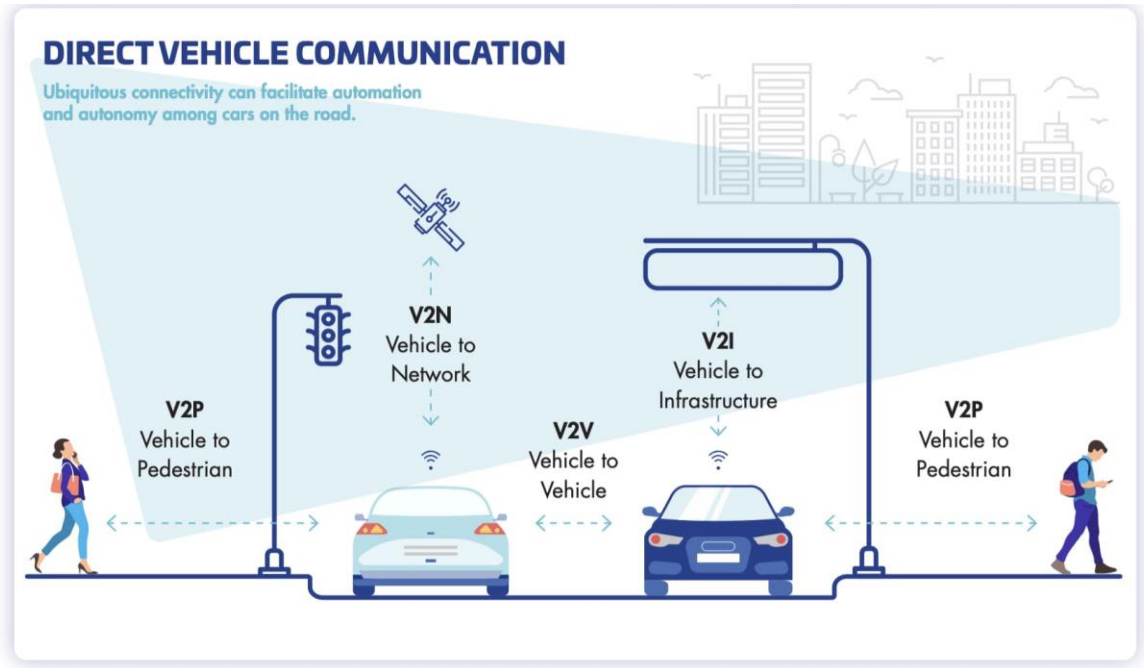


Figure 29 Vehicle to everything (V2X) (Source: [95])

Direct vehicle communication can provide information about the road ahead which would resolve the problem with low sensor ranges and help inform vehicles about accidents, construction works on the road, traffic congestions or provides a warning on bad road conditions like ice or oil on the road.

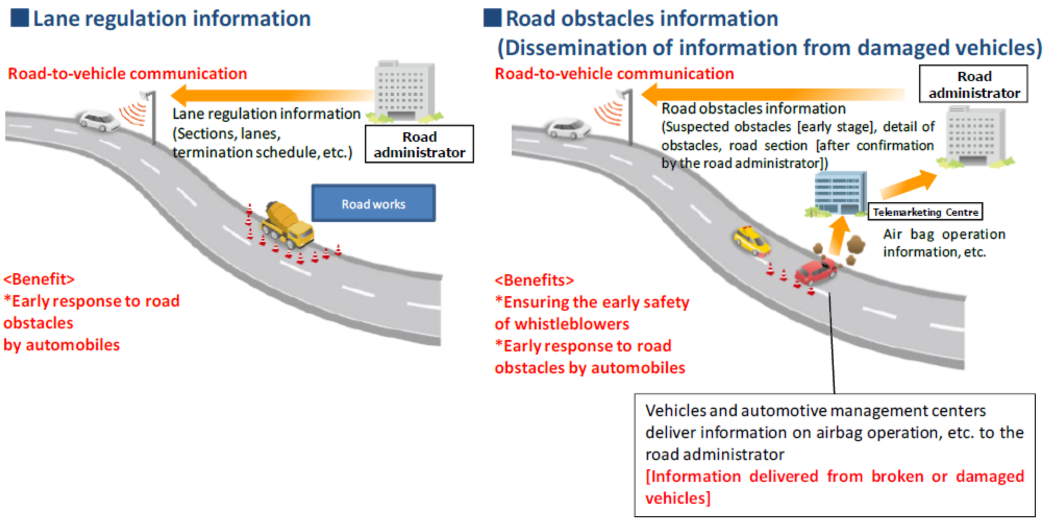


Figure 30 Information provision service on road ahead (Source: [27])

5.3. Digital Maps

Digital maps are specialized maps that provide additional information like road and traffic sign information to the vehicle to improve the reliability and functionality of ADAS systems. With higher automation levels also comes higher requirements. For that purpose so-called high-definition (HD) maps are used. Their accuracy is within a few centimetres and includes detailed information on road geometry, road borders, lane markings, lane connectivity, speed limits, traffic signs and many more. Those data are used together with the vehicle sensory to improve the reliability of ADAS.

Digital maps are provided normally by companies dealing with localization and mapping like TomTom or HERE. Those companies scan roads with specially equipped vehicles which scans are then converted to HD maps and stored in their cloud. Maps are then delivered to the vehicle by streaming directly or downloading to the vehicle's cloud or via Navigation Data Standard (NDS) format. To make the map readable from different distributors and ready for different systems and OEMs, there is a standardized protocol and interface called Advanced Driver Assistance Systems Interface Specification (ADASIS) which is maintained by the ADASIS forum, a non-profit international organization.

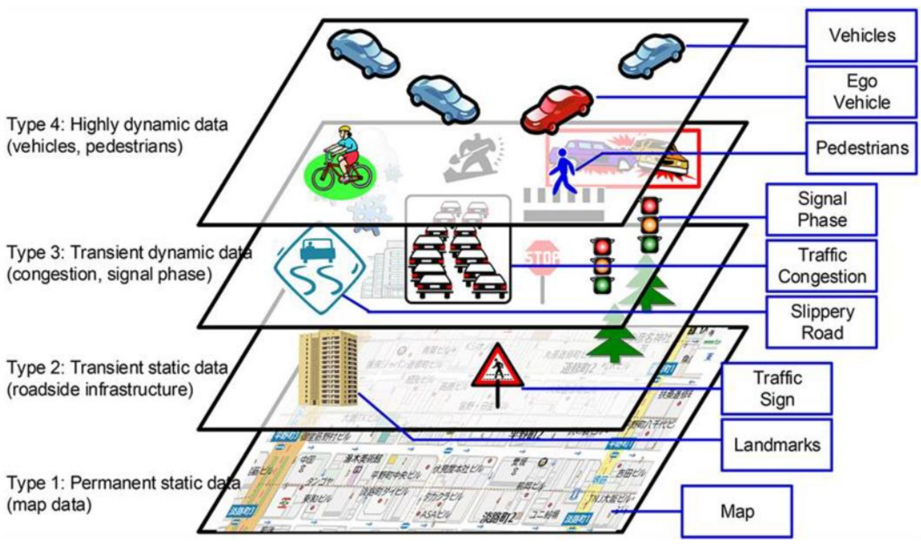


Figure 31 The four-layer local dynamic map model proposed in (Source: [96])

According to TomTom [97], there are three main fields of digital maps applications:

a) Localization

An automated vehicle must be able to precisely determine its position in regards to other static and dynamic objects. HD map in correlation with sensory can help in centimetre-precision longitudinal and lateral position predictions. Which helps ADAS to adjust its distance from adjacent objects.

b) Environment perception

The vehicle perceives its environment with sensory like cameras or LiDARs. But due to view blockage, harsh weather or light conditions it is hard to detect objects, moreover, it is hard to identify the environment in its right context. In that case, HD maps bring detailed information about road geometry regardless of environmental conditions and beyond sensors view range.

c) Path planning

For similar reasons like given above with help of HD, map vehicles can improve path planning as they provide a longer horizon and precise object positions.

Table 18 Benefits and challenges of using digital maps

Benefit	Description
Improved visibility	Digital maps are a valuable addition to the car's sensors. They provide map data far beyond the vehicle's sensor range. That helps to identify roads ahead and receive lane information's even if sensors are blocked or under poor visibilities due to weather conditions.
Lane elements	Digital maps provide information on lane boundaries, lane markings, lane centre lines, curbs, lane width, etc.
Road geometry	Road geometry like slope, curvatures, intersection information, etc.
Traffic signs	Digital maps include sign context such as speed limits.
Challenge	**Description**
Up to date	Digital maps should be quickly updated when traffic signs or lane markings are altered.
Limitation of AI	Automation of maps remains a problem and require manual revision by local road experts. To achieve higher quality, data-limited on-vehicle sensors and satellite imagery are not enough.
Size of datasets	HD maps are huge and require fast data transfer which is achievable currently only with 5G.

5.4. Specification needed

It is still a long way to go to achieve a fully-functional AV. Improvements are needed in all fields from vehicle technology and road infrastructure to regulations and laws.

Recently, the World Road Association (PIARC) prepared a report on challenges and opportunities for road operators and road authorities in the domain of automated vehicles [27]. The report summarizes the requirement for automated vehicles.

Table 19 Summary of needed specifications

Physical infrastructure	Description
Harmonization	Sensory manufacturers and carmakers have limited ability to customize software and sensor design for each jurisdiction. Data collection and analysis can benefit from smaller data sets. Therefore, there is a strong need for traffic signs and road markings harmonization.
Digitalization & Connectivity	Harmonization is not an easy task, ADAS still have many limitations. Digitalization of road infrastructure and V2X communication can bring further support and redundancy.
Standardization of static and dynamic signs	TSRS is influenced by the design of signs, their sizes, colour as well as the refresh rate of electronic signs. TSRS is also unable to recognize variable and changeable message signs. To support digitalization and future ADAS features, more strict standards would need to be defined.
Lane marking	To improve the performance of AV several measures for lane markings are suggested. To help with localization, one idea is to use landmarks to provide information on the exact location. To move AV predictable, others suggest having dedicated lanes just for AV (this is applicable for a transition period in presence of mixed traffic). To deal with control overtaking from system to human in higher levels of driving automation, it is suggested to build security areas and emergency stop areas along the road.
Awareness of vehicle dynamic limits	With higher levels of driving automation where systems bear full responsibility for driving tasks, a system will also need to deal with precise determination of road conditions and vehicle dynamic limits to perform safe and comfortable manœuvres. For that purpose, it is required to develop high-quality friction and vehicle dynamic estimator with vehicle sensors and V2X communication.
Maintainance strategy	The current system highly depends on well-maintained road infrastructure. For the future of AD, it is crucial to define a sustainable maintenance process and allocate sufficient fundings to road authorities.
Additional connectivity requirements	Undeniably, connectivity is one of the essential trends. But to achieve proper support to AD precise information in real-time must be passed between AV and the environment. Therefore, data transmission requirements are low latency and big data rate (currently, only achievable with 5G). Other accompanying requirements are to ensure sufficient funds to train personal, cover investment, operating and maintenance costs for infrastructure as well as decide on communication fees.

6. CONCLUSION

Creating safer roads and sustainable mobility with automated driving is undeniable the major trend that shapes our present and future. Market penetration of the automated driver assistance systems (ADAS) and advances in new laws that support automated driving is another evidence of acceptance of automated driving. Still, many challenges need to be overcome to bring ADAS to the next level. Road infrastructure is one of them. Thus, a broader understanding of ADAS and road infrastructure synergy is needed.

This report aims to support the Commission's work with MS' experts in establishing common specifications for road markings and signs. This report is the third part of the study in establishing common road markings and signs specifications for human drivers and ADAS.

Therefore, the following information is provided: 1) background information on automated driving and challenges; 2) overview of state-of-the-art existing ADAS technology; 3) Estimates and trends of market penetration today and in the future; and 4) future trends and needed specifications.

From the analysis of the current technology, future trends and road infrastructure, it can be concluded that for vehicles up to SAE Level 2, where the human driver is just supported by the system and must be aware of the situation at all times, sufficiently is to hold quality and maintenance of the road markings and signs on a level that is adequate for humans. Reduced reliability can be expected in adverse weather conditions and poorly maintained infrastructure. For higher automation levels that require high reliability of the system, major changes in the maintenance process, regulation, standardization and even re-design of road infrastructure would be needed. Thus, to further define specifications for higher levels of automation, a more detailed analysis is needed.

REFERENCES

[1] Hedges & Company, "How many cars are there in the world in 2021?," 2021. [Online]. Available: https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/. [Accessed 4 Nov. 2021].

[2] World Health Organization, "Road traffic injuries," 2021. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries.

[3] "McKinsey & Company," [Online]. Available: https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/overview.

[4] R. Decae, C. Goldenbeld and F. Hermens, "Road Safety Targets Monitoring - EC.EUROPA.EU," European Commission, 2021.

[5] Vision Zero Network, "Vision Zero Network," [Online]. Available: https://visionzeronetwork.org/. [Accessed 25 October 2021].

[6] A. Eichberger, E. Tomasch, W. Hischberg and H. Stefan, "Potenziale von Systemen der aktiven Sicherheit und Fahrerassistenz.," *ATZ-Automobiltechnische Zeitschrift,* vol. 113, no. 7, pp. 594-601., 2011.

[7] K. D. Kusano and H. C. Gabler, "Comparison of Expected Crash and Injury Reduction from Production Forward Collision and Lane Departure Warning Systems," *Traffic Injury Prevention,* vol. 16, p. S109–S114, October 2015.

[8] J. S. Hickman, F. Guo, M. C. Camden, R. J. Hanowski, A. Medina and J. E. Mabry, "Efficacy of roll stability control and lane departure warning systems using carrier-collected data," *Journal of Safety Research,* vol. 52, p. 59–63, February 2015.

[9] S. Sternlund, "The safety potential of lane departure warning systems—A descriptive real-world study of fatal lane departure passenger car crashes in Sweden," *Traffic Injury Prevention,* vol. 18, p. S18–S23, May 2017.

[10] R. Spicer, A. Vahabaghaie, G. Bahouth, L. Drees, R. Martinez von Bülow and P. Baur, "Field effectiveness evaluation of advanced driver assistance systems," *Traffic Injury Prevention,* vol. 19, p. S91–S95, December 2018.

[11] J. B. Cicchino, "Effects of lane departure warning on police-reported crash rates," *Journal of Safety Research,* vol. 66, p. 61–70, September 2018.

[12] AAA Foundation, "Potential Reduction in Crashes, Injuries and Deaths from Large-Scale Deployment of Advanced Driver Assistance Systems," 2018.

[13] P. Penmetsa, M. Hudnall and S. Nambisan, "Potential safety benefits of lane departure prevention technology," *IATSS Research,* vol. 43, p. 21–26, April 2019.

[14] H. Tan, F. Zhao, H. Hao and Z. Liu, "Estimate of safety impact of lane keeping assistant system on fatalities and injuries reduction for China: Scenarios through 2030," *Traffic Injury Prevention,* vol. 21, p. 156–162, February 2020.

[15] TomTom International BV, "Intelligent Speed Assistance," 2021. [Online]. Available: https://www.tomtom.com/use-cases/intelligent-speed-assistance/.

[16] Dotdash, "Self-Driving Cars Could Change the Auto Industry (GM, F)," 2019. [Online]. Available: https://www.investopedia.com/articles/personal-finance/031315/selfdriving-cars-could-change-auto-industry.asp. [Accessed 5 Nov. 2021].

[17] E. Thorn, S. C. Kimmel, M. Chaka and B. A. Hamilton, "A framework for automated driving system testable cases and scenarios.," United States. Department of Transportation. National Highway Traffic Safety Administration., 2018.

[18] SAE J3016, "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles," 2018.

[19] Automated Vehicle Safety Consortium, "AVSC Best Practice for Describing an Operational Design Domain: Conceptual Framework and Lexicon.," SAE Industry Technologies Consortia, 2020.

[20] INFRAMIX consortium, "Infrastructure Categorization: ISAD levels," 2017. [Online]. Available: https://www.inframix.eu/infrastructure-categorization/. [Accessed 5 Nov. 2021].

[21] W. Wachenfeld and H. Winner, "The release of autonomous vehicles.," in *Autonomous driving*, Berlin, Heidelberg, Springer, 2016, pp. 425-44.

[22] CONNECTED AUTOMATED DRIVING EUROPE, "Standards Collection," 2021. [Online]. Available: https://www.connectedautomateddriving.eu/standards/standards-collection/.

[23] ASAM, [Online]. Available: https://www.asam.net/. [Accessed 6 Nov. 2021].

[24] AASHTO Journal, "AAA: Distracted Driving Increases with ADAS Technology," 2019. [Online]. Available: https://aashtojournal.org/2019/12/20/aaa-distracted-driving-increases-with-adas-technology/. [Accessed 12 Nov. 2021].

[25] C. Kaufmann, M. Frühwirth, D. Messerschmidt, M. Moser, A. Eichberger and S. Arefnezhad, "Driving and tiredness: Results of the behaviour observation of a simulator study with special focus on automated driving.," *Transactions on transport sciences,* vol. 11, no. 2, pp. 51-63, 2020.

[26] E. Awad, S. Dsouza, R. Kim, J. Schulz, J. Henrich, A. Shariff, J. Bonnefon and I. Rahwan, "The moral machine experiment," *Nature,* vol. 563, no. 7729, pp. 59--64, 2018.

[27] PIARC, "Task Force B.2 Automated Vehicle: Challenges and opportunities for road operators and road authorities," 2021.

[28] American Automobile Association, "Advanced driver assistance technology names: AAA's recommendation for common naming of advanced safety systems.," AAA News Room 25, 2019.

[29] "Lane Keeping Assist System (LKAS)," [Online]. Available: http://techinfo.honda.com/rjanisis/pubs/QS/AH/BTY31919GW/enu/GUID-A94041EB-E74D-4902-BEF4-1CF4CA97EC55.html. [Accessed 02 Nov. 2021].

[30] E. Martí, M. A. de Miguel, F. García and J. Pérez, "A review of sensor technologies for perception in automated driving.," *IEEE Intell. Transp. Syst. Mag.,* vol. 11, no. 4, p. 94–108, 2019.

[31] The Next Web B.V., "3 improvements needed to make our autonomous car future a reality," [Online]. Available: https://thenextweb.com/news/3-improvements-needed-make-autonomous-car-future-reality. [Accessed 7 October 2017].

[32] Traffic sign recognition explained, [Online]. Available: https://www.carexpert.com.au/car-news/traffic-sign-recognition-explained.

[33] A. Dubey, "Stereo vision-Facing the challenges and seeing the opportunities for ADAS applications.," *Texas Instruments Technical Note ,* 2016.

[34] N. Druml, I. Maksymova, T. Thurner, D. van Lierop, M. Hennecke and A. Foroutan, "1D MEMS micro-scanning LiDAR," in *In Conference on Sensor Device Technologies and Applications (SENSORDEVICES) (Vol. 9)*, 2018.

[35] Geodetics, "LiDAR Intensity: What is it and What are it's applications?," [Online]. Available: https://geodetics.com/lidar-intensity-applications/. [Accessed 02 Nov. 2021].

[36] Velodyne Lidar, "A Guide to Lidar Wavelengths for Autonomous Vehicles and Driver Assistance," 2018. [Online]. Available: https://velodynelidar.com/blog/guide-to-lidar-wavelengths/. [Accessed 02 Nov. 2021].

[37] Velodyne Lidar, "Velodyne Lidar," 2021. [Online]. Available: https://velodynelidar.com/. [Accessed 02 Nov. 2021].

[38] Xenomatix, "Xenomatix," [Online]. Available: https://xenomatix.com/. [Accessed 2 Nov. 2021].

[39] A. Baker-Campbell, "Fair Weather Friend: How do LiDAR Systems Cope in Rain & Fog?," Gearhead Media, LLC, [Online]. Available: https://www.autovision-news.com/sensing/sensor-technology/lidar-systems-rain-fog/. [Accessed 09 Nov. 2021].

[40] A. Hillel, R. Lerner, D. Levi and G. Raz, "Recent progress in road and lane detection: a survey.," *Machine vision and applications,* vol. 25, no. 3, pp. 727-745, 2014.

[41] H. Zhu, K. V. Yuen, L. Mihaylova and H. Leung, "Overview of Environment Perception for Intelligent Vehicles," *IEEE Transactions on Intelligent Transportation Systems,* vol. 18, no. 10, pp. 2584 - 2601, 2017.

[42] S. P. Narote, P. N. Bhujbal, A. S. Narote and D. M. Dhane, "A review of recent advances in lane detection and departure warning system.," *Pattern Recognition,* vol. 73, pp. 216-234, 2018.

[43] J. Tang, S. Li and P. Liu, "A review of lane detection methods based on deep learning.," *Pattern Recognition,* vol. 111, 2021.

[44] J. G. Wang, C. J. Lin and S. M. Chen, "Applying fuzzy method to vision-based lane detection and departure warning system.," *Expert systems with applications,* vol. 37, no. 1, pp. 113-126, 2010.

[45] P. Y. Hsiao, C. W. Yeh, S. S. Huang and L. C. Fu, "A portable vision-based real-time lane departure warning system: day and night.," *IEEE Transactions on Vehicular Technology,* vol. 58, no. 4, pp. 2089-2094, 2008.

[46] X. Wang, Y. Wang and C. Wen, "Robust lane detection based on gradient-pairs constraint.," *Proceedings of the 30th Chinese Control Conference.,* pp. 3181-3185, IEEE 2011.

[47] H. Y. Cheng, B. S. Jeng, P. T. Tseng and K. C. Fan, "Lane detection with moving vehicles in the traffic scenes.," *IEEE Transactions on intelligent transportation systems,* vol. 7, no. 4, pp. 571-582, 2006.

[48] I. Katramados, S. Crumpler and T. P. Breckon, "Real-time traversable surface detection by colour space fusion and temporal analysis.," in *International Conference on Computer Vision Systems*, Berlin, Heidelberg, Springer, 2009, pp. 265-274.

[49] J. M. Álvarez, A. M. López and R. Baldrich, "Shadow resistant road segmentation from a mobile monocular system.," in *Iberian Conference on*

Pattern Recognition and Image Analysis, Berlin, Heidelberg, Springer, 2007, pp. 9-16.

[50] Pomerleau, "RALPH: Rapidly adapting lateral position handler.," in *Proceedings of the Intelligent Vehicles' 95. Symposium*, IEEE, 1995, pp. 506-511.

[51] A. Broggi and S. Cattani, "An agent based evolutionary approach to path detection for off-road vehicle guidance.," *Pattern Recognition Letters,* vol. 27, no. 11, pp. 1164-1173, 2006.

[52] G. Zhang, N. Zheng, C. Cui, Y. Yan and Z. Yuan, "An efficient road detection method in noisy urban environment.," in *2009 IEEE Intelligent Vehicles Symposium*, IEEE, 2009, pp. 556-561.

[53] S. J. Wu, H. H. Chiang, J. W. Perng, C. J. Chen, B. F. Wu and T. T. Lee, "The heterogeneous systems integration design and implementation for lane keeping on a vehicle.," *IEEE Transactions on Intelligent Transportation Systems,* vol. 9, no. 2, pp. 246-263, 2008.

[54] T. Ogawa and K. Takagi, "Lane recognition using on-vehicle lidar.," in *2006 IEEE Intelligent Vehicles Symposium*, IEEE, 2006, pp. 540-545.

[55] E. Forson, "edforson," 2017. [Online]. Available: https://edforson.me/posts/using-computer-vision-to-find-lane-lines-on-road/. [Accessed 9 Nov. 2021].

[56] C. Mu and X. Ma, "Lane detection based on object segmentation and piecewise fitting.," *TELKOMNIKA Indones. J. Electr. Eng. TELKOMNIKA,* vol. 12, no. 5, pp. 3491-3500, 2014.

[57] D. Ding, C. Lee and K. Y. Lee, "An adaptive road ROI determination algorithm for lane detection.," in *2013 IEEE International Conference of IEEE Region 10 (TENCON 2013)*, IEEE, 2013, pp. 1-4.

[58] E. Forson, "Teaching Cars To See — Advanced Lane Detection Using Computer Vision," toward data science, 2017. [Online]. Available: https://towardsdatascience.com/teaching-cars-to-see-advanced-lane-detection-using-computer-vision-87a01de0424f. [Accessed 9 Nov. 2021].

[59] K. Yamaguchi, A. Watanabe, T. Naito and Y. Ninomiya, "Road region estimation using a sequence of monocular images.," in *2008 19th International Conference on Pattern Recognition*, IEEE, 2008, pp. 1-4.

[60] R. Jiang, R. Klette, T. Vaudrey and S. Wang, "New lane model and distance transform for lane detection and tracking.," in *International Conference on Computer Analysis of Images and Patterns*, Berlin, Heidelberg, Springer, 2009, pp. 1044-1052.

[61] A. Borkar, M. Hayes and M. T. Smith, "Robust lane detection and tracking with ransac and kalman filter.," in *2009 16th IEEE International Conference on Image Processing (ICIP)* , IEEE, 2009, pp. 3261-3264.

[62] Z. Kim, "Robust lane detection and tracking in challenging scenarios.," *IEEE Transactions on intelligent transportation systems,* vol. 9, no. 1, pp. 16-26, 2008.

[63] J. Long, E. Shelhamer and T. Darrell, "Fully convolutional networks for semantic segmentation," *Proceedings of the IEEE conference on computer vision and pattern recognition.,* pp. 3431-3440, 2015.

[64] C. Farabet, C. Couprie, L. Najman and Y. LeCun, "Learning hierarchical features for scene labeling.," *IEEE transactions on pattern analysis and machine intelligence,* vol. 35, no. 8, pp. 1915-1929, 2012.

[65] V. Badrinarayanan, A. Kendall and R. Cipolla, "Segnet: A deep convolutional encoder-decoder architecture for image segmentation.," *IEEE transactions on pattern analysis and machine intelligence,* vol. 39, no. 12, pp. 2481-2495, 2017.

[66] Mathworks, [Online]. Available: https://blogs.mathworks.com/wp-content/uploads/2017/10/LabeledLanes.png. [Accessed 9 Nov. 2021].

[67] T. E. Burghardt, R. Popp, B. Helmreich, T. Reiter, G. Böhm, G. Pitterle and M. Artmann, "Visibility of various road markings for machine vision.," *Case Studies in Construction Materials,* vol. 15, p. e00579, 2021.

[68] S. B. W. e. al., "Vision-Based Traffic Sign Detection and Recognition Systems: Current Trends and Challenges," *Sensors,* vol. 19, no. 9, 2019.

[69] Potters Industry and Mobileye , "Pavement Markings Guiding Autonomous Vehicles - A Real World Study.," 2016. [Online]. Available: https://higherlogicdownload.s3.amazonaws.com/AUVSI/14c12c18-fde1-4c1d-8548-035ad166c766/UploadedImages/documents/Breakouts/20-2%20Physical%20Infrastructure.pdf.

[70] European Union Road Federation (2013), "Marking the Way Towards a Safer Future," Brussels: ERF.

[71] M. Hadi, P. Sinha and J. R. Easterling IV, "Effect of environmental conditions on performance of image recognition-based lane departure warning system.," *Transportation research record,* vol. 2000, no. 1, pp. 114-120, 2007.

[72] A. Pike, S. Clear, T. Barrette, T. Hedblom and J. Whitney, "Effects of the Wet Retroreflectivity and Luminance of Pavement Markings on Lane Departure Warning in Nighttime Continuous Rain with and without Glare Sources.," *SAE Technical Paper,* Vols. 2019-01-1014., 2019.

[73] S. O. Lundkvist and C. Fors, "Lane Departure Warning System - LDW," *Linköping: VTI,* 2010.

[74] P. J. Carlson and M. Poorsartep, "Enhancing the Roadway Physical Infrastructure for Advanced Vehicle Technologies: A Case Study in Pavement," *Proceedings of Transportation Research Board 96th Annual Meeting,* 2017.

[75] T. E. Burghardt, R. P. B. Helmreich, T. Reiter, G. Boehm, G. Pitterlec and M. Artmann, "Visibility of road markings to machine vision – climatic wind tunnel experiment," 2021.

[76] Texas A&M Transportation Institute , "Evaluation of The Effects of Pavement Marking Characteristics on Detectability by ADAS Machine Vision.," NCHRP Project 20-102(6), 2018.

[77] EuroRAP & Euro NCAP, "Roads That Cars Can Read," 2011. [Online]. Available: http://www.eurorap.org/wp-content/uploads/2015/04/20110629-Roads-That-Cars-Can-Read-June-2011.pdf..

[78] Austroads, "Implications of Pavement Markings for Machine Vision," 2020. [Online]. Available: https://austroads.com.au/publications/connected-and-automated-vehicles/ap-r633-20..

[79] C. G. Roh, J. Kim and I. Im, "Analysis of Impact of Rain Conditions on ADAS.," *Sensors,* vol. 20, no. 23, 2020.

[80] D. Babić, D. Babić, M. Fiolić and Ž. Šarić, "Study, Analysis of Market-Ready Traffic Sign Recognition Systems in Cars: A Test Field," *Energies,* vol. 14, no. 12, 2021.

[81] S. B. Wali, M. A. Abdullah, M. A. Hannan, A. Hussain, S. A. Samad, P. J. Ker and M. B. Mansor, "Vision-Based Traffic Sign Detection and Recognition Systems: Current Trends and Challenges," *sensors,* 2019.

[82] J. Gangadharan, "https://www.eetindia.co.in/solve-traffic-sign-recognition-challenges/," 2016. [Online].

[83] M. Seraj, A. Rosales-Castellanos, A. Shalkamy, K. El-Basyouny and T. Z. Qiu, "The Implications of Weather and Reflectivity Variations on Automatic Traffic Sign Recognition Performance," *Journal of advanced transportation,* 2021.

[84] "Huge opportunity as only 10% of the 1 billion cars in use have ADAS features," 2021. [Online]. Available: https://www.canalys.com/newsroom/huge-opportunity-as-only-10-of-the-1-billion-cars-in-use-have-adas-features.

[85] "Level 2 autonomous driving Q4 2020 and full year 2020," [Online]. Available: https://www.canalys.com/newsroom/canalys-autonomous-driving-starts-to-hit-mainstream-as-35-million-new-cars-had-level-2-features-in-q4-2020.

[86] J. Scholliers, M. Tarkiainen, A. Silla, M. M. R. Janse and G. v. d. Born, "Study on the feasibility, costs and benefits of retrofitting advanced driver assistance to improve road safety," 2020.

[87] K. Nuthall, "European Automakers Facing Deadline for Adding Safety Features," 24 01 2020. [Online]. Available: https://www.wardsauto.com/safety-technology/european-automakers-facing-deadline-adding-safety-features.

[88] Honda Motor Europe Ltd., "Honda erhält Zulassung für das autonome Fahren auf Level 3," Nov. 2020. [Online]. Available: https://hondanews.eu/ch/de/cars/media/pressreleases/319692/honda-erhalt-zulassung-fur-das-autonome-fahren-auf-level-3?utm_campaign=Syndicated_319692&utm_medium=RSS_Alle%20Pressemitteilungen&utm_source=hondanews.eu. [Accessed 14 Nov. 2021].

[89] JD Supra, LLC, "Germany takes the lead with a new law on autonomous driving and update," [Online]. Available: https://www.jdsupra.com/legalnews/germany-takes-the-lead-with-a-new-law-7746782/. [Accessed 14 Nov. 2021].

[90] Roland Berger GmbH, "Advanced Driver-Assistance Systems: A ubiquitous technology for the future of vehicles," 2021. [Online]. Available: https://www.rolandberger.com/en/Insights/Publications/Advanced-Driver-Assistance-Systems-A-ubiquitous-technology-for-the-future-of.html. [Accessed 10 June 2021].

[91] J. Kocić, N. Jovičić and V. Drndarević, "Sensors and Sensor Fusion in Autonomous Vehicles," in *2018 26th Telecommunications Forum (TELFOR)*, IEEE, 2018, pp. 420-425.

[92] D. J. Yeong, G. Velasco-Hernandez, J. Barry and J. Walsh, "Sensor and Sensor Fusion Technology in Autonomous Vehicles: A Review," *Sensors,* vol. 21, no. 6, p. 2140, 2021.

[93] J. Fayyad, M. Jaradat, D. Gruyer and H. Najjaran, "Deep Learning Sensor Fusion for Autonomous Vehicle Perception and Localization: A Review," *Sensors,* 2020.

[94] Z. Wang, Y. Wu and Q. Niu, "Multi-Sensor Fusion in Automated Driving: A Survey," *IEEE Access,* vol. 8, pp. 2847-2868, 2020.

[95] Thales Group, "V2X: What is Vehicle to Everything?," 2021. [Online]. [Accessed 10 Nov. 2021].

[96] H. Shimada, A. Yamaguchi, H. Takada and K. Sato, "Implementation and evaluation of local dynamic map in safety driving systems.," *Journal of Transportation Technologies,* vol. 5, no. 02, p. 102, 2015.

[97] TomTom International BV, "How do HD maps extend the vision of autonomous vehicles?," 220. [Online]. Available: https://download.tomtom.com/open/banners/Elektrobit_TomTom_whitepaper.pdf. [Accessed 8 Nov. 2021].

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Innovation, new technologies & future trends

Final report of the WP4

January, 2022

Directorate-General for Mobility and Transport
Study on road signs and road markings

SUMMARY

In the last decade, a significant effort has been devoted to improving all aspects of road safety. All these improvements have been driven by the increase of road safety awareness and the implementation of contemporary road safety strategies which, among other, seek to improve the road infrastructure and vehicle safety systems. Since the objective of this study is to assess the possibility of establishing common specifications for road markings and road signs in order to improve their readability and detectability, both for human drivers and ADAS, it is important to identify and analyse the ongoing innovation and research activities related to road markings, road signs and Advanced Driver Assistance Systems (ADAS) technologies.

In terms of vehicles, this paper analyses several technologies, such as vehicular communication, digital maps, smart infrastructure, cloud-computing, cooperative driving and sensor fusion. In terms of road markings and road signs, it provides an insight into developments related to materials used for road markings and signs, the uniformity and standardisation of road markings and signs, and other innovations and technologies which may improve their detectability and readability in the future.

Overall, this report provides a comprehensive overview of innovation trends and new technologies in the field of ADAS technologies, road markings and road signs.

CONTENTS

1. INTRODUCTION

With the development of a new approach to EU road safety policy, along with a medium-term Strategic Action Plan, the European Commission seeks to reaffirm the ambitious long-term vision and goal: moving close to zero deaths by 2050. To achieve the planned target, the Commission decided to base its road safety policy framework on the "Safe System" approach. This approach changes the paradigm that "death and serious injury in road accidents are an inevitable price to be paid for mobility" into a view that accidents with the aforementioned consequences are largely preventable. Prevention is rooted in a layered combination of measures related to safe infrastructure, safe vehicle systems, safe road use and better post-crash care.

Since roadway characteristics and the vehicle itself may provoke human error and thus be the primary cause of a road crash instead of preventing it, a significant effort has been devoted to improving vehicle safety systems and infrastructure with the aid of technological breakthroughs in the last decade.

In general, automated driving is one of the fastest-growing industry trends which can potentially bring many social and economic advantages, such as an increase in road safety, higher commuting comfort, transport for elderly and disabled persons, less pollution by increasing traffic efficiency etc. Indisputably, safety is the primary motivator for transport automation but at the same time its greatest challenge. During the last decade, a wide range of driver support features have been developed, all with the aim to assist drivers and minimise safety risks in driving. One of the most common Advanced Driver Assistance Systems (ADAS) are Lateral Support Systems (LSS) and Traffic Sign Recognition System (TSRS), which rely on the elements of road infrastructure, i.e., road markings and road signs.

Traditionally, the main task of road markings and road signs, as one of the fundamental elements of road infrastructure, was to provide timely and necessary information about the upcoming situation to human drivers. In other words, they warn and inform drivers about the conditions and characteristics of the road, guide road users through the traffic network and regulate traffic in a safe way. However, with the development of the aforementioned vehicle safety systems, road markings and road signs have become a valuable source of information for certain ADAS technologies as well.

Therefore, although widely used for more than 100 years, in the last decade a significant amount of research interest focused on road markings and road signs and their development. The main motivation behind these research activities, as stated, is the increase of road safety awareness and the implementation of contemporary road safety strategies which seek to improve the road infrastructure in order to facilitate the needs of all drivers, as well as the needs of evolving vehicle technologies.

Thus, the overall aim of this study is to provide the Commission with up-to-date information to support the work of the MS' experts, through five working packages:

1. Review and preparation of an inventory of current practices and procedures regarding road markings and road signs;
2. Supporting the work of the MS' expert group;
3. Technology review of driver assistance technologies;

4. Innovation, new technologies and future trends related to ADAS technologies, road markings and road signs;
5. Gap analysis and recommendations.

Since the objective of the study is to assess the possibility of establishing common specifications for road markings and road signs in order to improve their readability and detectability, both for human drivers and ADAS, it is important to identify and analyse the ongoing innovation and research activities related to road markings, road signs and ADAS technologies. Innovation and research activities presented in this report were identified based on literature research and consultation with relevant stakeholders active in the aforementioned fields.

As the first step, we analysed relevant future trends related to ADAS technologies. This includes several technologies such as vehicular communication, digital maps, smart infrastructure, cloud computing, cooperative driving and sensor fusion. In addition, we considered relevant market trends in ADAS technologies and their market potential, as well as possible limitations and barriers.

The second step included identifying main innovations, new technologies and future trends related to road markings. These trends mainly pertain to improving road marking quality in terms of their visibility and durability, and their other aspects regarding materials and uniformity. The report also presents other innovations, such as "smart" or luminescent road markings.

The third step involves identifying new technologies and future trends related to road signs. This section contains an analysis of developments regarding retroreflective materials used for road signs and new technologies, such as QR, RFID and radar. In addition, the report addresses the work done within the UNECE Global Forum for Road Traffic Safety (WP.1) on the harmonisation of the Vienna Convention on Road Signs and Signals as well as other emerging innovations related to road signs.

Finally, this report provides an analysis of the state of play of digital road markings and road signs and studies their improvement potential and their likely impact from the perspective of drivers of both conventional vehicles and those equipped with ADAS.

2. FUTURE TRENDS OF ADAS TECHNOLOGIES

To ensure adequate reliability of ADAS technology, it is not sufficient to solely count on onboard sensors. Therefore, advanced technologies also rely on road infrastructure, vehicular communication and digitalisation of road markings and road signs.

2.1. Relevant trends

ADAS technology and automated driving (AD) are trends gaining more and more interest from the industry and researchers. Several technologies show promising improvements in AD reliability, which is a necessary characteristic in order to bring automation to a higher level. Those technologies are outlined as follows.

- *Vehicular communication*: Communication between the vehicle and other traffic participants and roadside units (RSU). In general, we can refer to it as vehicle-to-everything (V2X). However, it can be divided into more specific direct vehicle communication types, such as vehicle-to-pedestrian (V2P), vehicle-to-network (V2N), vehicle-to-vehicle (V2V), vehicle-to-infrastructure and vice versa (V2I/I2V), etc.

- *Digital maps*: Digital maps are layers built on top of a base and navigation maps. They contain information about the road ahead, traffic conditions, speed limits, road signs, and more. Their main task is to support localisation and provide perception beyond onboard sensor ranges.

- *Smart infrastructure*: V2I and RSU belong to smart infrastructure. However, this can also include other technologies, such as those related to infrared visible sign codes that are not visible to humans but only to infrared cameras, RFID or radar technology implemented on road signs, or smart road markings that incorporate micro/nano sensors.

- *Cloud computing*: Besides just storing data received from vehicles or RSU, cloud-based technology can support computing tasks that would, to some extent, remove this burden from the vehicles. In this way, the powerful computing infrastructure does not take place within vehicles and the system can focus on driving tasks.

- *Cooperative driving*: Single vehicles and drivers coordinate driving behaviour according to traffic and act cooperatively. An example of cooperative driving is platooning, where a group of vehicles drives as one. Cooperative driving can be enhanced through a higher level of connectivity and automation. The aim is to improve energy efficiency, traffic flow and safety.

- *Sensor fusion*: Sensor fusion enhances perception performance through inputs from multiple radars, LiDAR and cameras. Owing to the redundancy of sensors, safety is improved through reliability [1].

To benefit from these technologies, they need to achieve higher market penetration. Yet, this is somewhat of a vicious circle. Many vehicle manufacturers have the technology to move towards SAE L2+, but to successfully bring it to market they need acceptance, regulations that allow higher automation levels on the road, and prepared infrastructure for V2X and digital maps to support reliability. Reliability and safety of such systems are crucial to achieving acceptance. However, to place their products on the market and to gain profit, the telecommunication companies and digital map providers need more vehicles that support their technologies. With more such vehicles, many services could be provided to support cooperative driving and vehicular communication that would enhance safety, comfort and energy efficiency, and of course, contribute to people gaining trust in these systems.

2.2. Market review

2.2.1. Global ADAS market

Since road safety is one of the main social challenges of today, the ADAS market is rapidly growing. It is further boosted due to the upcoming safety regulations in Europe, North America and Asia-Pacific which mandate that new vehicles be equipped with at least some ADAS features, and increasing demand for automated driving systems. Although the COVID-19 pandemic has significantly affected the automotive industry, it is expected that the ADAS market will experience significant growth in the following years.

At the end of 2020, only around 10% of vehicles worldwide and around 19% of vehicles in Europe were equipped with ADAS features [2], [3]. However, in 2021 the overall worth of the ADAS market amounted to USD 27.2 billion, and it is expected to grow to USD 58.6 billion by 2028 at a Compound Annual Growth Rate (CAGR) of 11.4% [4]. Moreover, a study [5] based on interviews with Tier 1 manufacturers, automotive suppliers and industry experts concluded that by 2025, 85% of vehicles produced globally will have the level of automation L1 and above, while penetration of L4 or L5 features will not be more than 1%. Furthermore, L3 and higher features will account for only 10-15% of total ADAS penetration, whereas L2 features will achieve over 30% penetration across all regions. Finally, due to the aforementioned regulations, the study concluded that Europe is expected to have the greatest penetration of new ADAS vehicles sold by 2025. On the other hand, some predict that the Asia-Pacific ADAS market will hold the largest share by 2030, which can be attributed to high vehicle production and increased use of advanced electronics in Japan, South Korea and China [4].

When it comes to the types of ADAS systems, Adaptive Cruise Control (ACC) will hold the major share of the ADAS market in the years to come. The use and efficiency of ACC are particularly correlated with Traffic Sign Recognition System (TSRS). As for used technologies, ADAS features rely on different sensors such as LiDAR, radar or camera. Since radar is used in most systems, it is expected to be the fastest-growing component type sales by 2030 [4].

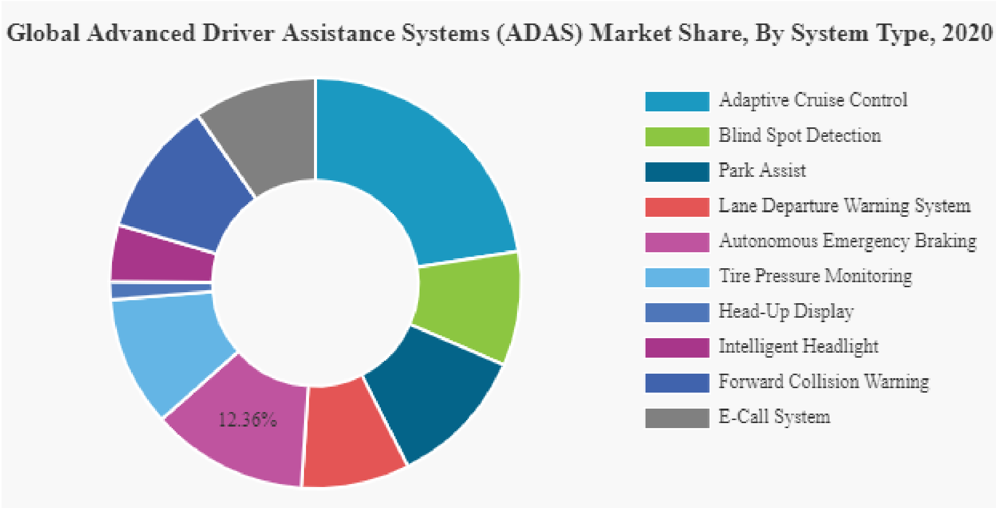


Figure 1 Market share by system type (Source: [4])

One of the limitations identified by Original Equipment Manufacturers (OEMs) for the deployment and development of new ADAS systems is the difficulty to design a global solution comprising different regulations and regional needs. This difficulty is a key-enabler for Europe, at least, to determine and define common regulations for each belonging country. Additionally, certain aspects of ADAS features on their own can limit their potential growth and deployment. As previously stated, ADAS features are based on different types of sensors. The sensors use batteries, which entails possible battery disturbances. Electronic components can also lead to some misfunctioning and, last in order but not in importance, these systems are exposed to cybersecurity threats with potentially dramatic outcomes. Battery consumption management, electronic components' reliability and cybersecurity threats are some of the challenges OEMs need to tackle in the following years.

2.2.2. Sensor fusion

The growing trend of autonomous vehicles and ADAS coupled with the constant need to improve safety for road users led to the deployment of sensor fusion in new vehicles. The sensor fusion market is projected to be worth USD 1.5 billion by 2025. As seen in Figure 2, Asia-Pacific is the fastest-growing region on the globe in terms of sales of sensors for autonomous driving with around 35% of the market’s growth [6]. Mitsubishi Electric Corp., NXP Semiconductors NV, Robert Bosch GmbH, Siemens AG and Valeo are identified as major players in the autonomous sensor market. However, one of the factors limiting the deployment of sensor fusion is the lack of standards. Lack of standardisation will ultimately increase the complexity of the devices in the coming years.

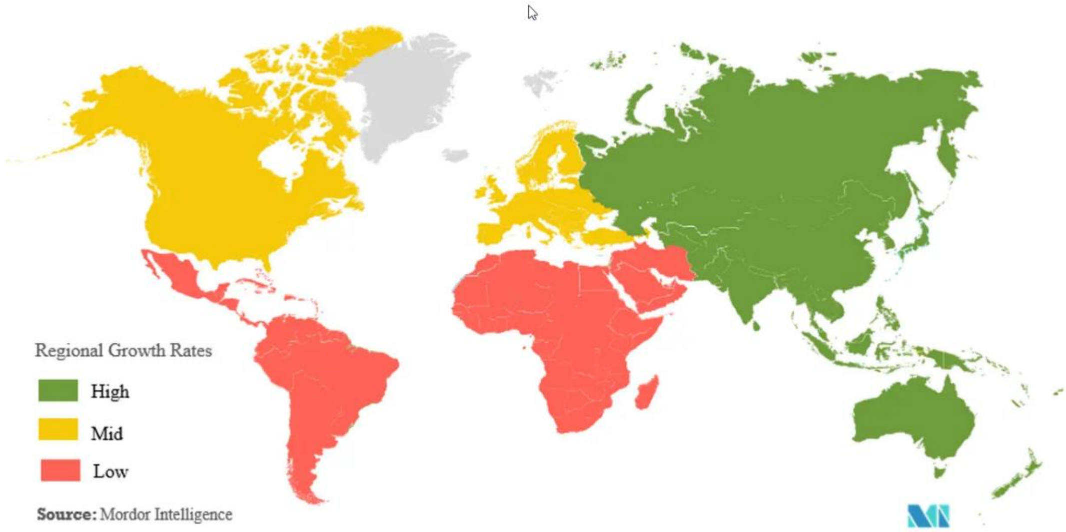


Figure 2 Sensor fusion market - growth rate by region (2020-2025) (Source: [7])

2.2.3. Vehicular communication

We mentioned the importance of V2X in the next decades and its impact on road safety. However, since it is an emerging technology, it lacks regulation. Today, there are two competing technologies: vehicular communication protocols like Dedicated Short-Range Communication (DSRC) and the cellular-based one, using C-V2X, 4G or 5G connectivity. Without any regulation in place, manufacturers will have to deal with both technologies for the time being. However, regulations aimed at minimising carbon emissions are seen as an encouraging factor for the development of V2X, coupled with the constant need to improve road safety, fuel savings and traffic efficiency.

According to a study conducted by Fatpos Global, the V2X market is expected to be worth around USD 6.7 billion by 2030 at a CAGR of 41.7% over the considered period 2021-2030 [8]. The major players in the V2X market include Continental AG, Infineon Technologies AG, Toyota Motor Corporation, Delphi Automotive PLC, Savari Technologies Pvt. Ltd., Denso Corporation, Volkswagen AG, General Motors Company, Daimler AG and BMW Group.

2.2.4. Digital maps

Digital maps are considered one of the most promising technologies in the years to come. Due to an increasing trend in automated driving development, the demand for digital mapping solutions is significantly growing. According to a study conducted by LP Information, the global HD maps market is worth about USD 1 billion in 2021 and is expected to reach almost USD 3 billion at a Compound Annual Growth Rate (CAGR) of 15% by 2028 [9].

The global HD maps for automated vehicles market is further segmented based on [10]:

- Solution - the market is classified into cloud-based and embedded, with the cloud-based segment holding the largest market share.
- Level of Automation – the market is classified into semi-automated (Level 2&3) and automated (Level 4&5). As stated earlier (see chapter 1.2.1), it is estimated that the semi-automated (Level 2&3) segment holds the largest market share.

- Vehicle Type - the market is classified into passenger and commercial vehicles, with the passenger vehicles segment holding the largest market share.
- Services - the market is classified into Advertisement, Localisation, Mapping and Update & Maintenance. The localisation segment is estimated to hold the largest market share.
- Geography - North America accounts for the largest share of the market, followed by Asia-Pacific with China and India as the main drivers for growth.

When it comes to the major players, companies such as HERE, Tomtom, Nvidia, Maxar are considered leaders in the HD maps sector for the years to come. However, other initiatives are emerging. In 2020, CARMERA and Toyota Research (TRI-AD) have partnered to develop an Automated Mapping Platform with the first automated driving mappings in Japan and the US. A more detailed description of digital maps is provided in Section 5.

2.3. Limitations and obstacles for the ADAS market

In terms of deployment and market penetration, ADAS systems face several obstacles:

- the technology behind ADAS systems;
- standardisation, regulation and liability;
- public acceptance;
- security of ADAS systems.

2.3.1. The technology behind ADAS systems

In terms of technology, all ADAS systems are based on sensors. These sensors can be cameras, LiDAR, RADAR, etc. Unfortunately, the lack of defined standards is one of the factors limiting the deployment of sensor fusion, despite the growing trend of autonomous vehicle development. Without standardisation, we will witness a significant increase in the complexity of devices in the coming years.

Lack of standardisation is also a problem for the technology used in V2X communications. Currently, there are two competing technologies: Dedicated Short-Range Communication (DSRC) and cellular-based communication, using 4G or 5G connectivity. With no standards in place, manufacturers will have to deal with both technologies for the time being.

It is also necessary to enhance the trustworthiness of the systems. Despite technological advances in the last decade, AV systems still need to be improved, particularly in situations of bad visibility or complex traffic.

2.3.2. Standardisation, regulation and liability

One of the limitations OEMs identified for the deployment and development of new ADAS systems is the difficulty to design a global solution comprising different regulations and regional needs. This problem is a key-enabler for Europe, at least, to determine and define common regulations for each belonging country.

A major issue to address is liability in case of an accident. It is difficult to determine who is liable for the accident: the driver or the car manufacturer. Usually, when a car crash happens, the victim pursues a claim based on the driver’s negligence. However, if the car was on “autopilot” at the time of the crash, the driver may not have been negligent, but the crash happened only due to a defect in the vehicle, leading to the liability of the car manufacturer.

2.3.3. Societal acceptance

Societal acceptance of automated vehicles is closely linked with other obstacles to their deployment. Based on literature review, Jing et al. identified several main factors that affect the acceptance of automated vehicles [11]. Of course, safety is the primary factor, followed by a performance-to-price value, mobility, value of travel time, symbolic value and ecological aspects. Also, the authors found substantial differences in attitudes toward automated driving depending on the part of the world (for example, between Europe and Asia). However, when examining public acceptance, not only passengers in automated vehicles should be considered but also other road users, particularly the vulnerable ones.

2.3.4. Security

As mentioned earlier, V2X communication is a key enabler for AV but unfortunately, it also brings weaknesses. Since they are more connected than traditional vehicles, AVs are more exposed to security breaches and potential cyberattacks that could have dramatic outcomes. Fortunately, as of July 2022 new vehicles will have to have cyber security type approval before being commercialised. Hopefully, it will help to increase trust in AVs.

Despite a lot of progress made in the last years, AVs still need to reach full public acceptance. Emerging norms, regulations and legislative progress will help in achieving this. In addition, standardisation is the key point for the deployment of AVs.

3. INNOVATION, NEW TECHNOLOGIES & FUTURE TRENDS RELATED TO ROAD MARKINGS

Although widely used for more than 100 years, during the last decade, road markings experienced a significant amount of research interest focused on different aspects of their development. An increase in road safety awareness and implementation of contemporary road safety strategies aimed at improving the road infrastructure in order to facilitate the needs of all drivers, combined with evolving vehicle technologies, are pushing toward new materials, techniques and technologies related to road markings. This section identifies and analyses the main innovations, new technologies and future trends based on literature research and consultations with relevant stakeholders. The aforementioned trends mainly relate to the improvement of road marking quality in terms of their visibility and durability, and their other aspects by improving the materials used. Some innovations, such as luminescent or "smart" road markings, have shown a certain potential. In the following sections, we present and discuss these trends.

3.1. Road marking materials

In general, road markings are systems consisting of two main components: a pigmented layer and reflective elements. The pigmented layer is the base material in which reflective materials are added in order to achieve a desirable retroreflectivity. Several materials are used worldwide for road markings, each of them presenting certain strengths and weaknesses. Individual materials mainly differ in terms of the application method and process, service life, price, coating thickness and structural characteristics.

Due to the aforementioned differences, it is quite difficult to unambiguously classify available road marking materials. One way of classifying the materials involves the use of solvent and in this way road markings are usually classified as solvent-borne, water-borne and solvent-free. In terms of durability, road marking materials can be classified as standard (conventional), durable and temporary products. Another way of classifying road marking materials is based on their retroreflection level under wet and rainy conditions [12]. Classification is also often based on the application thickness and usually materials are classified into thin or thick-layer materials. However, the most common way of classifying road marking materials is based on the material itself, i.e., type of material. In that sense, materials are usually classified as paint, plastic materials (thermoplastic and cold plastic) and tapes [12]. As stated in the first paragraph, each material has its characteristics, i.e., strengths and weaknesses.

Although the aforementioned materials have been used for decades now, in the last ten years significant improvement has been made in their general quality, application processes, durability, ecological aspects (the cradle-to-grave impact), visibility etc. One such example includes the so-called self-cleaning road marking paints. In general, self-cleaning coatings based on photocatalytic and super hydrophobic mechanisms gained a lot of interest in different industries in recent years. Such mechanisms are achieved in road markings using photocatalytic titanium dioxide (TiO_2), which combined with UV light from sunlight or fluorescence source, offers two unique properties: strong oxidation power and super-hydrophilicity [13]. Strong oxidation power is used to clean dirt attached to the paint, while super-hydrophilic property allows dirt to be easily washed off with water or rainfall [13]. This can help to achieve higher daytime and night-time visibility. However, there are still many concerns related to the real applicability of such materials and further testing and development are needed.

Recently significant efforts have been made in improving water-borne paints. Water-borne paints have water as their main solvent and dry with the evaporation of water from the material. As such, they are environmentally friendly, with significantly lower amounts of Volatile Organic Compound (VOC) compared to solvent-borne paints [14]. Although first commercialised in the 1980s, their use has been limited mainly due to the sluggish drying, very slow development of washout resistance and their durability which was often lower compared to other materials [12], [14]. However, developments in binder and additives recently led to significant improvements in the quality of water-borne paints. According to the study conducted in Croatia, such fast drying and high-quality water-borne paints were able to achieve desired quality levels even two years after the application [15]. Due to ecological benefits, thicker film layer and longer durability compared to solvent-borne paints, a relatively lower price compared to plastic and tape materials and ease of application, water-borne paints show promising potential, at least for certain areas and roads. In some countries, such as Scandinavian countries, the United States or Australia, this has already been put into practice to a certain extent[16]. Overall, the share of high-quality water-borne paints could significantly increase in the future precisely due to ecological requirements and standards as well as their performance which exceeds one of their solvent-borne counterparts, primarily by maintaining flexibility to provide longer-term adhesion to the road and the reflective materials (glass beads).

However, despite the many advantages of water-borne paints, there are still several other factors that constrain their use. One is related to the application machinery. Due to the high pH of high-quality water-borne paints, any metal parts of the application equipment that contact the paint must be made of stainless steel, which means that in many cases there is an initial capital investment in switching from solvent to water-borne paint. Due to the higher price compared to solvent-borne paints, in countries where no ecological regulations exist, cheaper solutions will often be used. Also, under adverse conditions for water-borne paint application, such as high humidity and low air flow, solvent-borne paints have a drying time advantage. Due to the risk of washout, the applicators must be properly trained and must understand the limitations of the systems [12]. Nevertheless, recent advances in their quality and performance should enable better visibility and longer durability (compared to solvent-borne paints) which should ultimately bring about safety benefits and optimisation of maintenance activities while enhancing the detectability and readability by both human drivers and ADAS systems.

In addition to the conversion from solvent to water-borne paints (at least to a certain degree), it is expected that future trends in road markings will be directed to higher use of structural (agglomerate) road markings and the development of new designs and patterns for them. The main advantage of structured road markings is primarily their higher visibility in wet and rainy conditions. In general, during wet or rainy conditions, the water layer often covers the road marking layer (especially in the case of thin-layer road markings) and the incident light from the headlamps is refracted as it travels first from the air into the water and then again refracted the second time as it goes from the water into the glass bead, which thus significantly reduces the visibility of the road marking [17].

On the other hand, structured road markings have 3-5 mm thicknesses and different design patterns ("tear drop", dotted, stochastic etc.) which improve the water drainage from the road marking, thus also improving its visibility in the aforementioned conditions (Figure 3). Moreover, structured markings provide "sheltering" to a part of glass beads from the direct action of tyres and snow ploughs, which additionally increases their service life [18]. In addition to higher visibility and longer service life, structured road markings provide additional safety benefits by producing a vibroacoustic effect that warns drivers when they depart from their lane [19]. However, such acoustic effects may not be desirable in settled areas where high sound levels and tonal components may disturb the people living close to the road [20].

An additional benefit of structured road markings is the fact that when their visibility levels fall under desirable levels, but the structure of the road marking remains intact, their performance can be renewed with thin-layer (usually 0.3–0.4 mm) applications of paint or with sprayed cold plastic [18]. In such a way, road markings can be refurbished while still retaining adequate water drainage effect and thus a certain level of visibility in wet and rainy conditions.

a)

b)

c)

d)

Figure 3 Examples of structured road marking patterns – a) regular drop-shaped; b) dotted pattern; c) stochastic transverse pattern; d) stochastic lengthwise pattern (Source: [20])

Besides structured road markings, a significant effort has been devoted to the development of the so-called all-weather road markings in the last decade. These road markings are marketed as highly visible under daytime, night-time and both dry and wet weather conditions. Some studies indicated that such road markings may provide safety benefits because they significantly increase detectability and readability for both human drivers and machine-vision systems [21]–[24]. However, it has to be noted that some all-weather materials may not provide desired results and that their visibility, especially in wet conditions, may be significantly reduced within a relatively short period [25], [26]. Nevertheless, further development of all-weather road markings is expected in the following years which, apart from enhancing their quality and durability, will also reduce their price.

In addition to road marking material, a crucial component of the whole system includes reflective elements, i.e., glass beads. Glass beads have two main functions: 1) they enable retroreflection and thus night-time visibility of road markings, and 2) they protect the base layer (road marking material) from abrasion [27]. Thus, it is evident that the quality of glass beads plays a significant role in the overall visibility and durability of road markings. In the last couple of years, significant efforts have been devoted to improving their quality and it is reasonable to expect that this trend will continue in the future.

Standard glass beads are made of recycled window glass and thus have a refractive index (RI) of 1.5, providing retroreflection of approximately 400 mcd/m^2/lx (for white road markings) [18]. They meet all the requirements in terms of roundness, clarity, air inclusions, contents of heavy metals and metalloids, and other properties defined by the European standard EN 1423 [28]. Commercially they are often used due to their price [29]. However, standard glass beads in combination with certain materials (thin-layer materials such as paint) may not have desirable visibility in wet and rainy conditions

[17]. On the other hand, high-quality glass beads are produced from virgin glass and have higher RI (1.6 up to 2.4). They also have very high roundness (> 90%), high surface quality, minimised air inclusions, and improved resistance to scratching, which ultimately results in high retroreflectivity that can go up to 1000 mcd/m^2/lx (for white road markings) [18]. However, the production of such glass beads is exceptionally difficult, and in combination with higher costs of raw material (virgin glass) it significantly increases their price compared to standard glass beads [18], [29].

Although high-quality glass beads show great potential for enhancing the night-time visibility of road markings, before their implementation one has to take into account which type of road marking material is being used and what is the expected thickness of that material after application. As stated at the beginning of this section, road markings are systems consisting of pigmented layer (road marking material) and reflective elements (glass beads), thus both components have to be taken into account when deciding on a specific system. Recent studies have shown that a proper combination of road marking material and glass beads may enhance the visibility and durability of road markings [18], [30], [31]. Although such systems have high initial costs, due to their longer service life compared to standard systems they would need fewer maintenance activities in the long term which would, according to the aforementioned studies, result in lower consumption of raw materials and thus similar or even lower maintenance costs compared to standard systems. Nevertheless, the application of such systems on all roads and in all climate regions may not have desirable cost-benefit effects and their use should be well considered before the application taking into account different aspects such as road type, traffic volume, climate conditions, available budget, desired service life etc.

Overall, the main trends in road marking development are expected to focus on improving and developing high-quality systems which will be more resilient to wear and tear and have longer service life while providing desirable levels of visibility in different conditions. Moreover, due to specific traffic and weather conditions on some roads, and in some regions and countries, developing tailor-made systems may be a potential solution in order to achieve desired quality and durability levels that ensure adequate detectability and readability by both human drivers and machine-vision systems. Besides the aforementioned, other innovative solutions for road markings are emerging, which are discussed in the following sections.

3.2. Uniformity and standardisation of road markings

In terms of detectability and readability of road markings by both human drivers and ADAS, potential problems may emerge due to the lack of uniformity and standardisation of road markings. Although road markings in Europe are regulated by the Vienna Convention on Road Signs and Signals (1968), the European Agreement supplementing the Convention (1971) and different EU standards, there are still differences among Member States. This is particularly evident when it comes to road marking design and legal requirements. While the design itself may not play a crucial role, legal requirements concerning road marking visibility in different conditions are more important for their desired detectability and readability by both human drivers and ADAS. Establishing a common approach on the EU level regarding road markings may bring additional safety benefits and further promote the uptake of ADAS technologies in the EU. However, such an approach should be evaluated and supported by a cost-benefit analysis, which is part of ongoing activities within this study.

3.3. “Smart” road markings

In terms of automated driving, communication between the vehicle, the infrastructure, and other vehicles is crucial. Vehicle-to-Infrastructure (V2I) communication represents the data exchange between the vehicle and the road infrastructure, where infrastructure components such as road markings, road signs and traffic lights can provide valuable information to vehicles, and vice versa.

In this sense, “smart” road markings, i.e., road markings with embedded sensors, is a technology that has been recently tested and which shows potential for further development and use. As stated, such road markings are primarily intended for Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) communication, and may provide guidance for vehicles when road markings are covered in rain and snow or when standard machine-vision systems used for lane detection and recognition fail to detect road markings.

In 2017 Texas Transportation Institute in collaboration with Virginia Tech Transportation Institute tested the use of RFID tags embedded into road markings. The testing vehicle was equipped with two antennas and an RFID reader, while specially designed RFID tags were placed in the 5 mm x 5 mm sensor grooves below the road marking (Figure 4) [32]. Overall, the results were promising, and the antennas detected the tags even in rainy conditions and over a longer period (over six months). However, the performance of the system was reduced during snow conditions.

Similar work was done within the “SAFE STRIP” project [33], [34]. The aim of the project was to test and develop different approaches for creating self-explanatory roads for all road users and all vehicle generations. However, more concrete inputs are lacking.

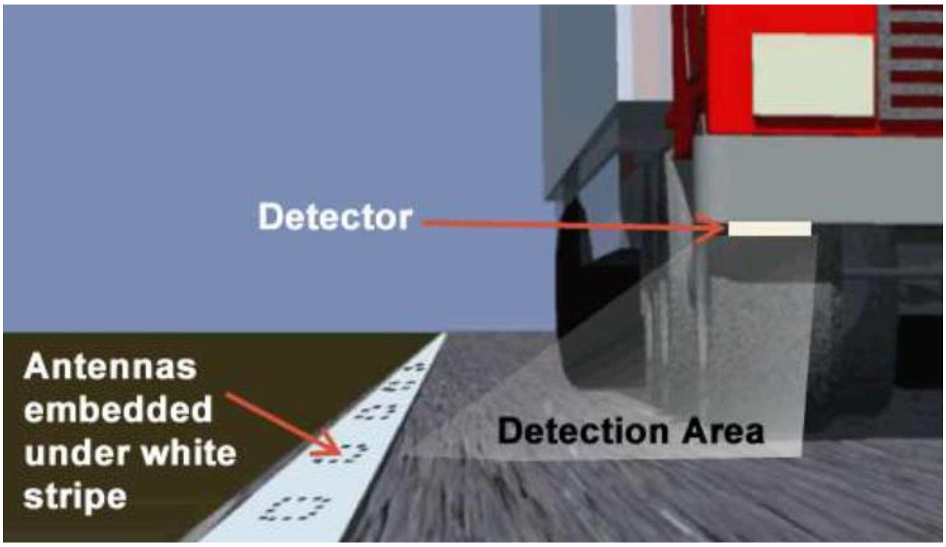


Figure 4 RFID tags embedded in the road marking (Source: [32])

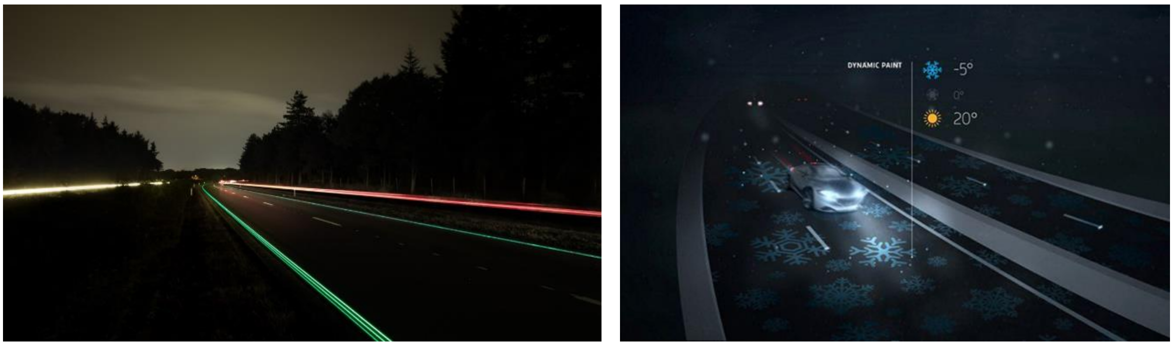
Although still in the stage of early development and testing, and without more solid evidence regarding the functionality of embedded sensors in road markings, such technology may provide additional benefits related to the detection of road markings by vehicles, especially in bad weather conditions. As stated in Section 2, sensor fusion is one of the most promising trends in ADAS technology, and sensors embedded in road markings may provide redundancy when standard lane detection sensors fail to detect road markings. However, such solutions need to be low-cost, durable and easy to apply. Overall, the integration of low-cost micro/nano sensors into road markings potentially may reduce the need for costly infrastructural elements and support the development of more intelligent and cost-effective road infrastructure.

3.4. Luminescent road markings

In recent years several efforts were made toward developing luminescent road markings which would replace standard road marking materials and glass beads. Luminescent road markings use special "photo-luminising" powder which charges during the day and slowly emits a green light during night-time. The so-called “glowing line” was first applied in the Netherlands, in the municipality of Oss, approximately 100 km southeast of Amsterdam (Figure 5a) [35].

A wider application of this material was also considered, and developers suggested that it may be used to warn drivers about specific road conditions. For example, when the temperature drops below a certain level, snowflake symbols may appear on the road (Figure 5b).

However, engineers who applied luminescent road markings stated that they were sensitive to large amounts of moisture due to rainfall and that before their further application it is important to clarify how far in advance the road markings could be seen, how skid resistant and how visible during the day they should be and how they would perform in winter when there are fewer hours of daylight [36].



a) b)

Figure 5 Luminescent road markings implemented in the Netherlands (a) and potential application of such technology (b) (Source: [35])

Parallel to the trials in the Netherlands, the Scottish Road Research Board funded and published a report entitled "Investigating the Potential for Reactive 'Glowing' Roads as an Initiative on the Scottish Road Network". The report concluded that the innovation was not well developed at that time, but that there is potential for future development [37]. However, in 2018 a new report was published with the aim of researching, testing and evaluating the viability of the glow-in-the-dark strategy as an improvement to active travel routes in Scotland [38]. Overall, it was concluded that such "glowing" road markings are yet not developed enough to be used as a replacement for standard road marking materials. However, the study detected clear potential for further development and testing of such technologies.

Most recently (in 2020), Australian Government's Road Safety Innovation Fund granted OmniGrip Direct - Australia Wide and DM Roads with a three-year grant to research photoluminescent road marking for use on regional roads in order to increase the night-time visibility in an area with frequent high-density fog (Figure 6) [39]. Within the project, Safety Path Enhanced Visibility Linemarking was applied in Victoria (Australia), which represented the first application of the luminescent thermoplastic road markings.

Figure 6 Luminescent road markings applied in Australia (Source: [40])

Furthermore, in 2020 Nance and Sparks published a study in which they tested various protective coatings for improving luminescent road markings [41]. Since luminescent road markings are highly sensitive to water, the idea behind the research was to use coatings that create a protective shell preventing water from penetrating the phosphor surface, and thus improve the luminescence lifetime of phosphors. After conducting the experiments, the authors concluded that carboxylic acid functional groups are beneficial to the phosphor/paint system. This means that the coating paint system must adhere well to the phosphor in order to protect it from hydrolysis. Moreover, the authors emphasised that the thermodynamic and kinetic factors along with the selected functional group should provide information on how to adequately optimise durability, transparency, adhesion, compatibility and dispersion. Overall, it was concluded that when all parameters are optimised, the aforementioned material could be used for road markings.

Moreover, Villa et al. measured colour and luminance in the dark under constant illumination, under cyclic illumination and on real road markings in a controlled environment in order to test and evaluate photoluminescent paints used for road markings [42]. After conducting the experiments, the authors concluded that luminescent road markings may strengthen the visual guidance of drivers on the road by increasing the visibility distance beyond the headlamps range under favourable night-time lighting conditions and with traffic. Also, they emphasised that, depending on the conditions, luminance can last from a few minutes to a whole night. However, the authors highlighted the need for further testing and development of such materials before their application.

Overall, luminescent paints are an interesting innovation that shows some potential for road marking application. However, in its current state, this technology is not at the desired level when it comes to visibility (especially in wet and rainy conditions), durability and price. According to a review conducted by Nance and Sparks, the main challenges concern the stabilisation of particles in the paint matrix and the tendency of phosphor to hydrolyse [43]. Safety and ecological issues are also still not fully clear. In addition, the impact of such technology on driver behaviour and detectability and readability of road markings by machine vision is still unknown. Nevertheless, further research activities are expected in the future aimed at lengthening the luminescence lifetime and increasing the maximum luminescence of such road markings.

4. INNOVATION, NEW TECHNOLOGIES & FUTURE TRENDS RELATED TO ROAD SIGNS

As in the case of road markings, an increase in road safety awareness and implementation of contemporary road safety strategies, combined with evolving vehicle technologies, are the main driving forces behind the development of road signs. This section identifies and analyses the main innovations, new technologies and future trends based on literature research and consultations with relevant stakeholders. The aforementioned trends mainly relate to improving the quality of retroreflective materials for road signs in terms of visibility and durability. Significant work has been done regarding the uniformity and standardisation of road signs and the improvements of the Vienna Convention on Road Signs and Signals (1968). In addition, to improve the detectability and readability of road signs by ADAS, a lot of research activities focused on innovations related to the QR, RFID or radar technology and their use on road signs. Several other innovations such as retroreflective structural colour films or self-illuminating road signs are also presented.

4.1. Retroreflective materials for road signs

Conspicuity or visibility of road signs is one of their most important characteristics and it refers to how easy it is for drivers and road users to see and locate a road sign in the surrounding road environment [44]. During the day, due to enough ambient light and contrast, the detection of road signs, in general, does not represent a significant problem. However, the situation changes during low visibility conditions, especially for human drivers, which is why road signs are produced using retroreflective materials.

From their first application to today, retroreflective materials for road signs have undergone several improvements in order to facilitate higher retroreflection levels during low visibility conditions. Today there are two retroreflection technologies available on the market: beaded and prismatic technology. Both technologies return illumination from a headlamp back towards the driver. However, from the optical perspective, prismatic materials provide significantly higher retroreflection levels with better distribution of reflected light compared to beaded ones. Better performance and higher durability, combined with environmental reasons (less pollutants and used energy), are the main reasons why many manufacturers discontinued offering beaded materials and are focusing their production only on prismatic materials [45].

Since the luminance of a sign depends on many factors, such as the amount of light reaching the sign, retroreflection properties of the sign, the relative position of headlamps, sign, and driver as well as other factors (atmospheric and windshield transmissivity) [45], the main developments and innovations in road sign materials relate to enhancing the prismatic technology. In general, the quality of retroreflective materials for road signs is determined by their retroreflective properties, the orientation of retroreflected light, angularity (observation and entrance angle) and durability. Current materials can achieve high levels of retroreflection, however, it is more challenging to achieve desired retroreflection levels and orientation of retroreflected light when observation and entrance angles increase. Specifically, different vehicle types have their driving seat at different heights, and thus the observation angle of the driver changes which ultimately decreases the apparent luminance of a sign [46]. Moreover, the position of the sign significantly affects the entrance angle and thus the apparent luminance of the sign. Most of the light from the vehicle headlights focuses on the right side of the roadway, and thus the apparent luminance of signs located on that side will be the highest. If the same sign is placed on the left side of the roadway, it will be illuminated with around 30% of the light from the headlights, while if it is placed above the roadway it will get only around 20% of the light[1] [47]. Of course, the less light illuminating the sign, the less its apparent luminance will be.

Therefore, further development of retroreflective materials for road signs will focus on "fine-tuning" the prismatic technology. This means identifying the so-called "black spots" in micro-prims where light is not properly reflected and returned to its source, and redesigning the micro-prims in a way that the "black spots" are eliminated as much as possible. With these improvements and with the combination of differently shaped micro-prisms, the cone of reflected light can be modified. However, the challenge the manufacturers are facing is to micro-replicate and build the same properties for every part of the material surface. Overall, future trends will focus on enhancing the materials in order to achieve the desired levels of retroreflection for drivers of all vehicle types and regardless of the sign position. Such improvements should enable the detectability and readability of road signs mainly for human drivers but also for ADAS.

4.2. Uniformity and standardisation of road signs

Readability and comprehension of road signs depend on several factors, of which the design of the sign and its familiarity are among the most important ones. This is why road signs are standardised by international standards and regulations. As in the case of road markings, in Europe road signs are regulated by the Vienna Convention on Road Signs and Signals (1968), the European Agreement supplementing the Convention (1971) and different EU standards, whose main aims are to achieve international uniformity of road signs in order to facilitate international road traffic and to increase road safety [48]. Yet, inconsistency and lack of uniformity to some extent still exist.

A significant effort in reducing and eliminating those inconsistencies and general shortcomings of the Vienna Convention has been made through the work of the Global Forum for Road Traffic Safety (WP.1), whose primary function is to serve as guardian of United Nations legal instruments aimed at harmonising traffic rules. Under the Global Forum for Road Traffic Safety, an expert group has been created to review the Convention and to suggest ways that would lead to easier interpretation and more effective implementation of the Convention [49]. From its first meeting held in December 2013 until today, the expert group has had in total 20 meetings at which significant efforts were made in terms of identifying potential improvements to the Convention. In 2019, the expert group drafted a report with conclusions and recommendations regarding the identified inconsistencies and inaccuracies [50]. In total 36 issues were identified, of which some relate to the design of road signs, such as [50]:

- "*The Convention provides for some signs – e.g. signs for warning of intersections – many examples which may give the impression that the list of examples permitted in the Convention is exhaustive.*" (Issue 13);
- *"The units such as "tonnes" or "meters" are placed on images of signs in an inconsistent way, i.e. with or without the space between the digit and the unit."* (Issue 17);
- *"The Convention is missing some important signs, symbols and some additional sign variants. The Convention contains signs that appear not to be used."* (Issue 34);
- *"In the Convention, there are some signs and symbols that contain unnecessary details which compromise their legibility."* (Issue 36).

[1] The presented percentages may differ depending on the vehicle model and type of headlight.

Examples of identified inconsistencies in the design of road signs are presented in Figure 7. Although the stated differences may not pose significant problems for human drivers, they could be problematic for ADAS.

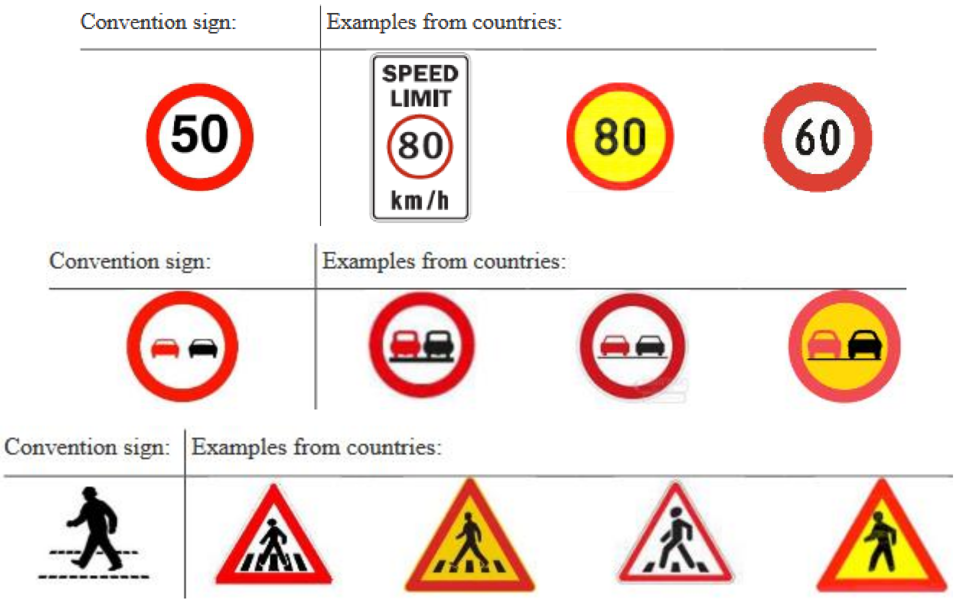


Figure 7 Examples of inconsistencies in the design of road signs identified by the expert group (Source: [50])

The work of the expert group also focused on the development of an openly accessible, internet-based Road Signs Management System and the creation of an electronic version of the Convention on Road Signs and Signals (e-CoRSS). As an interactive and searchable online platform, e-CoRSS could provide significant help to governing agencies, road authorities and road signs manufacturers in terms of sign design, possible options and combinations.

In addition to the improvements in consistency and uniformity of road sign design, a new EU standard regarding static road signs is expected. The current standard (EN 12899-1:2007) defines requirements for retroreflective materials, structural performance, partial safety factors (wind, dynamic snow, point and dead loads), deflections, sign plates and faces, transilluminated and externally illuminated signs (corrosion, electrical aspects, colours), labelling and marking, evaluation of conformity and test methods [51]. However, the standards cover only beaded retroreflective materials, while the requirements for prismatic materials are defined in the European Assessment Document [52]. The new standard will redefine requirements for all retroreflective materials on the market using a performance-based approach and improve testing methods.

Additional efforts, although not directly related to road sign standards, have been made in terms of developing a new legislative update to EU rules on Intelligent Transport Systems (ITS), in which a „Speed Sign Catalogue" has been established [53]. The catalogue comprises data regarding speed limits in Member States, which can primarily be used by the Intelligent Speed Assistance (ISA) to ensure more accurate information.

Overall, the EU approach to road sign design, which is based on symbols rather than text, is beneficial to both human drivers and ADAS [54]–[56]. However, further efforts are needed to improve the regulations, standards and norms in order to enhance the detectability and readability of road signs by both humans and ADAS. Nevertheless, the ongoing work on a new edition of the EN 12899-1 standard, as well as the work conducted under the Global Forum for Road Traffic Safety (WP.1) should bring about a significant contribution, and thus enable the further promotion of ADAS technologies in the EU.

4.3. QR, RFID and radar technology on road signs

New solutions for enhancing the detection and readability of road signs and for establishing Vehicle-to-Infrastructure/Infrastructure-to-Vehicle communication have recently started to develop in both theory and practice. Such developments mainly focus on the use of QR and RFID technology on road signs. The main idea behind these approaches is to bypass the shortcomings of machine vision regarding installation and maintenance, positioning, collocation and design of the signs, and different weather and lightning conditions.

a) QR codes

The potential use of QR codes on road signs has been proposed as an upgrade to the Traffic Sign Recognition System (TSRS). The main purpose of implementing QR codes on road signs is to combine the advantages of classical signs with the advantages of QR codes, and in such a way reduce or even eliminate most of the typical processing tasks needed for the classical TSRS, e.g. shape classification, colour and symbol identification [57]. The main advantage of this system is that it would be robust to the variations of viewing conditions, it would easily support real-time processing, and most importantly, it would support error correction in case of partially damaged or partially invisible signs. However, the implementation of QR codes on road signs should meet the specification regarding retroreflectivity and it should not significantly change the appearance of the sign. On the other hand, QR codes should have high contrast for machine-vision systems to accurately detect and decode them.

In 2017, a field experiment was conducted in a construction zone along Highway I-75 in Michigan in order to test the potential of such a technology. Specially designed QR codes were installed on 15 road signs (Figure 8) [58]. The code was made with optically transparent materials and thus it did not change the appearance of the sign to the human driver. The size of the code was approximately 65% of the surface area of the sign and its design was optimised in order to enable far and near readings and to ensure that critical information is conveyed to the vehicle even if the sign is partially obscured. A vehicle equipped with an IR light source and a camera that can read the QR code at a distance similar to that at which a human driver can read a traditional road sign was used. Overall, the reading distance was approximately 90 meters (measured while the testing vehicle was travelling at the posted speed limit), and no statistical differences in the reading distance were found in any of the conditions (white or orange background signs; daytime/night-time conditions). On the other hand, some differences in the reading distance were found depending on the lane the car was driving in relative to the sign. Finally, the retroreflection of the signs was measured and it met the specifications after 1,500 hours of accelerated weathering.

Figure 8 Example of visible and Near-IR view of QR code (Source: [58])

Such technology could be beneficial for ADAS and could assist in all tasks that provide redundancy to other sensor systems engaged in the vehicle. Thus, it could provide greater situational awareness, efficient transfer of dynamic information about changing roadway conditions, and improved localisation [58]. However, further developments and tests are needed in order to ensure the desired data payload efficiency, read distance, error correction, read confidence, as well as retroreflection and durability of the material. The technology itself has to be optimised based on the aforementioned factors in order to achieve the desired detection and readability in all weather and traffic conditions for both human drivers and ADAS.

b) RFID and radar technology on road signs

In addition to QR codes, a lot of research and tests have been done on the use of RFID technology on road signs. In general, the RFID system consists of three main components: an antenna or coil, a transceiver (with decoder), and a transponder, i.e. RFID tag electronically programmed with unique information [59]. One of the earliest studies related to RFID tags and their functionality as digital road signs which can be displayed in the vehicle was conducted in Japan in 2006 [60]. A total of 57 passive RFID tags were installed on the road close to road signs at 19 locations on the test track. The testing vehicle was equipped with an antenna for reading the RFID tags. After the tag was read, the software in the vehicle would show the data about the upcoming road sign. Although the employed tags had a maximum communication range of 40 cm, the data stored in all of the tags were recognised and displayed properly.

After this first implementation, several other studies evaluated the use of RFID technology on road signs as part of driving-aid systems [61]–[63]. In these studies, small active RFID tags containing a microchip programmed to transmit an identification code (unique to each sign) were placed on road signs. Since the tags were active, they were regularly (for example every 1.5 s) emitting identification signals. In addition, they were powered by their own batteries. Testing vehicles were equipped with antennas and RFID readers which read the tag before the vehicle reached the sign. The unique ID written on each RFID tag connects to the road sign database so that the sign's meaning and purpose can be recognised. After the sign has been recognised, it can be presented to the driver or used by different ADAS systems (for example Adaptive Cruise Control). An example of the configuration of the system is presented in Figure 9.

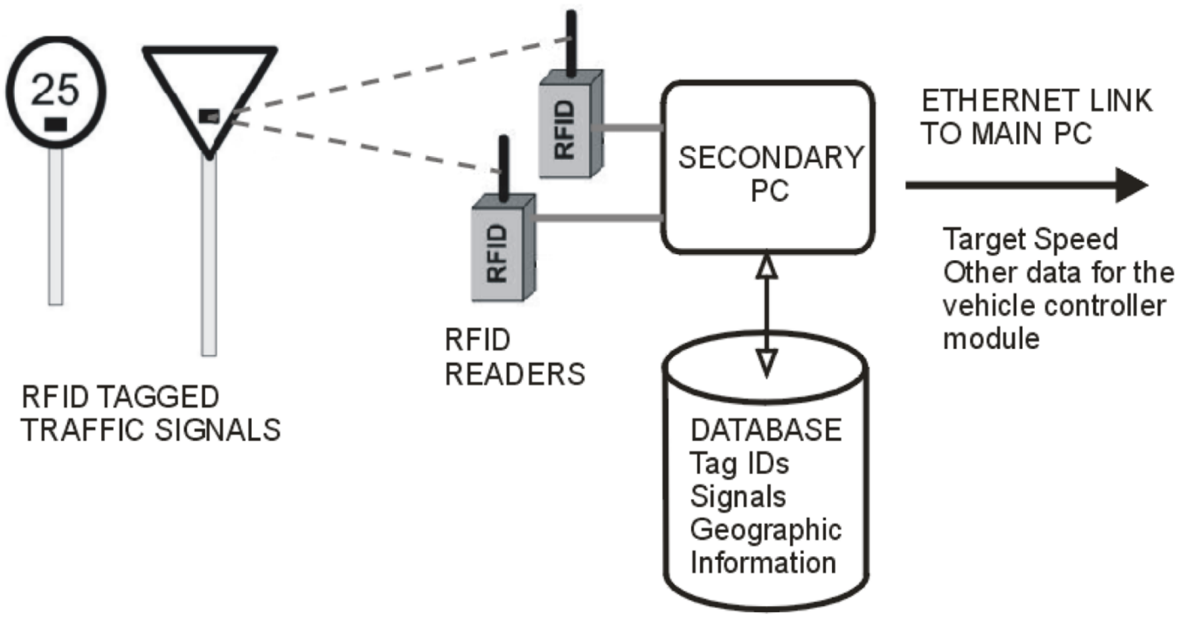


Figure 9 Block diagram of the RFID technology used for road signs (Source: [61])

RFID technology on road signs has also been tested for the purpose of maintaining road signs inventory [61], [64], [65]. In addition to road signs maintenance, the road signs inventory is highly necessary for the development of digital twins, i.e., maps of roads signs (discussed in more detail in Section 5). The whole system is similar to the one described in previous paragraphs, meaning that on each sign an RFID tag is placed which contains the unique identification code of the sign. The process starts when a reader device, installed in the inspection vehicle, either broadcasts requests for the tag identification (passive system) or the RFID tag itself emits the signal (active system). After the tag has been detected, the system then checks the detected tag against the original inventory in real-time and updates the database. In case of some discrepancies, they are reported to the road maintenance company. The basic concept of the system used for the road sign database inventory based on RFID technology is presented in Figure 10.

An automatic update of the road sign database using RFID technology has been partially implemented in Croatia on the state road network (road category below motorways). A pilot project showed that with the optimisation of RFID tag design and their placement on the sign, in combination with the number, the position and the type of antennas on the inspection vehicle, a 99% reading accuracy can be achieved even for signs located up to 6-7 m away from the road and at different driving speeds (up to 60 km/h) [66]. The project is currently ongoing, and wider implementation of passive RFID tags on road signs started in 2020. By 2022, approximately 80,000 RFID tags have been placed on road signs within the network of 3,750 km of state roads across Croatia.

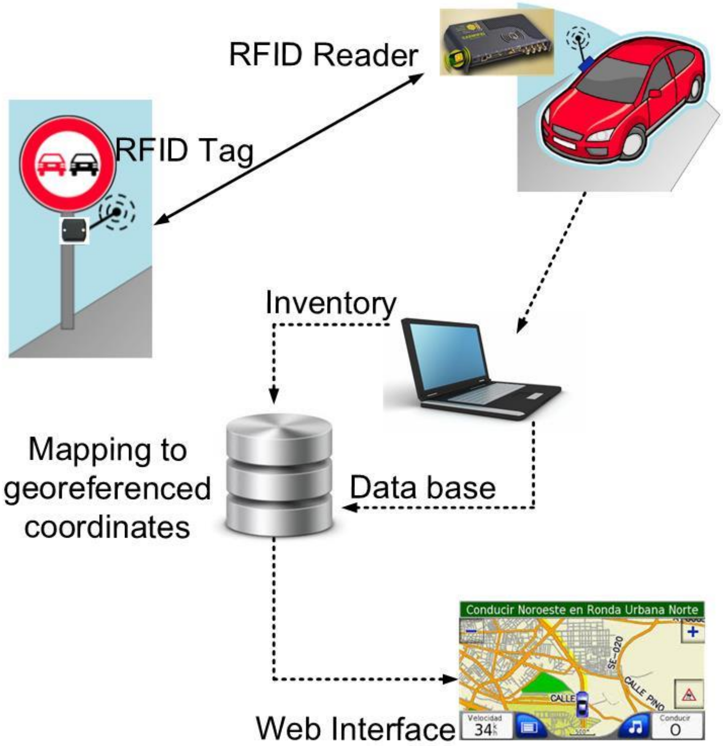


Figure 10 Schematic representation of the system used for the road sign database inventory, based on RFID technology (Source: [64])

Similar to RFID technology, a group of scientists in Poland recently developed "smart" road signs which can warn drivers about weather conditions and hazardous road conditions ahead of them. The technology is based on radar, sensors and Bluetooth. Each road sign has a built-in radar system that can send information to drivers by creating a Doppler effect (Doppler radar built-in road sign) which transmits pulses of radio waves directed at vehicles and other moving objects on the road (Figure 11). The main idea behind the technology is to send different messages to drivers (concerning speed limits, traffic congestion, work zone locations etc.). Apart from warning drivers, with the use of a Bluetooth Wi-Fi system, the technology would enable Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) communication [67].

Figure 11 Concept of communication between "smart" road signs and vehicles (Source: [67])

Overall, all the aforementioned studies and research activities show a promising potential of RFID and radar technology on road signs. The main advantages of both technologies are that they are relatively "simple" and well-known and could be implemented at a relatively low cost and minimum infrastructure maintenance. They could provide redundancy to other sensor systems engaged in vehicles and a high accuracy V2I and I2V communication in diverse weather and traffic conditions. However, more testing is needed in order to evaluate the full potential of RFID and radar technology for V2I/I2V communication and to determine the limitations and cost aspects of their implementation.

4.4. Other innovations related to road signs

Besides the innovations, technologies and potential trends in the field of road signs presented in previous sections, a few more novelties have been identified through literature review.

In 2019, Fan et al. published the results of their preliminary research on retroreflective structural colour films (RSCF) for road signs [68]. The innovation included a partially embedded monolayer of polymer microspheres on the sticky side of the transparent tape, which spontaneously forms interferometric structure on the surface of air-cushioned microspheres that can lead to unique structural colours and remain non-iridescent under coaxial illumination and viewing conditions, but appear iridescent under noncoaxial illumination and viewing conditions. The authors stated that such technology may be suitable for application on road signs in order to increase road safety, especially at night-time. A night-time experiment was conducted to further support the aforementioned statement that included a retroreflective structural colour film placed at a height of 1.7 m on the roadside, a moving vehicle with its headlights on, and a pedestrian walking toward the road sign. The difference between the slowly moving pedestrian and the vehicle is in the angle between the observer's line of sight and the axis of the headlight illumination of the road sign which varies with the position of the moving vehicle. That angle increases slowly when the vehicle is far from the sign and more rapidly as the vehicle comes closer to the sign. Thus, the pedestrian can see a nearly constant colour signal when the vehicle is far away but a dynamically changing colour signal when the vehicle is close by. That colour change can be used as a visual indicator or warning signal for both pedestrians and drivers. As fast-moving drivers pass by, their viewing angles change rapidly, resulting in a flickering colourful speed limit display. In that regard, a passive flickering coloured image could increase the awareness of speed limits or other road hazards and crashes. The described concept is presented in Figure 12:

- Photos A and B represent 1-m-long and 6-cm-wide RSCF fabricated from 15-µm monodisperse polystyrene micro-spheres, showing no colour under diffuse daylight (A) but a bright green colour under illumination by vehicle headlights at night (B);
- A schematic model of a night-time scene in which a 60-cm triangular road sign fabricated from RSCF is located on the roadside and illuminated by the headlights of a moving vehicle and a pedestrian is walking toward the traffic sign (C);
- Pedestrian's view of the road sign when the distance L between the vehicle and the sign is 80 m (D), 50 m (E), and 30 m (F), demonstrating a smart colour-changing visual indication that warns the pedestrian of the approaching vehicle;
- Driver's view of the road sign at distances L of 80 m (G), 50 m (H), and 30 m (I), demonstrating that the driver sees a saturated and stable colour signal.

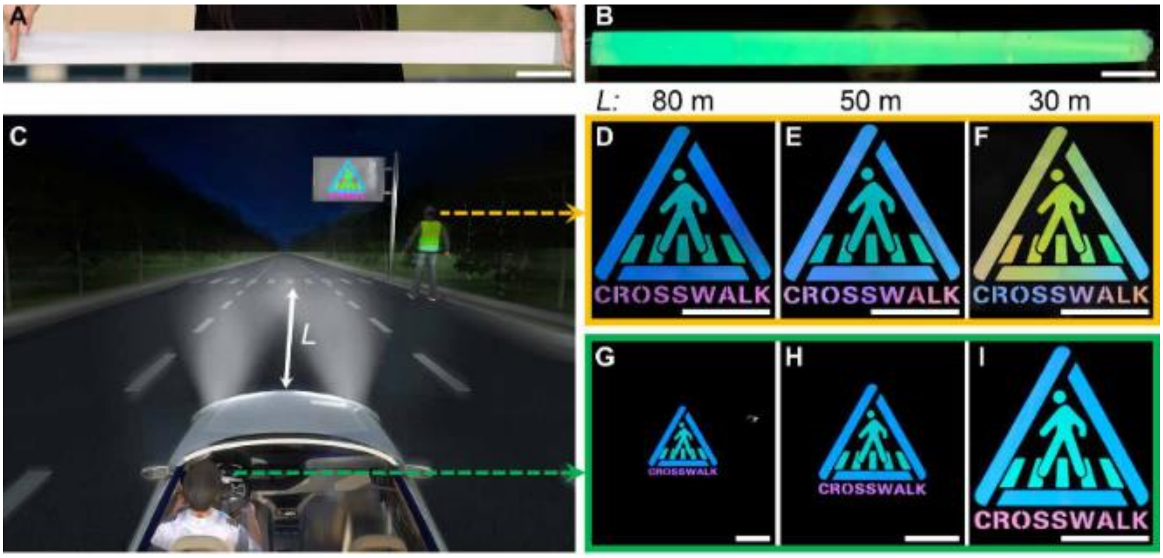


Figure 12 Proposed application of retroreflective structural colour films (RSCF) for road signs (Source: [68])

Furthermore, Rada et al. experimented with a similar technology that uses a thin film of microscale concave interfaces that reflects different colours of light [69]. By changing the angle of light entering individual "pixels", authors created tenable colour displays that could be seen by visual and infrared cameras and detected by LiDARs. Moreover, authors indicate that microscale concave interfaces structure technology, which has both retroreflection and iridescent features, may introduce a unique two-fold benefit – "*the IR laser of the LiDAR system will enable the angle-independent retroreflection response, while the visible imaging portion that relies on external light sources will experience an angle-dependent color changing signal that allows for visible pattern recognition*" [69].

While testing retroreflection and iridescent features of microscale concave interfaces structures, the authors designed a 3 × 3 square array using 9 different polystyrene microspheres. The colour patterns of these structures change with the change of the observation angle (driver's view). This effect can be observed in Figure 13b - the colour changes from purple to blue and green as the observation angle changes within the range of 0° to 35°. When illuminated with a LIDAR camera, the camera was able to clearly recognise the experimental sign with the IR camera (Figure 13d), however, the IR imaging condition differs from the visible one - the colour of the "STOP" sign produced using microscale concave interfaces structures changes with different observation angles, which is in contrast to the standard retroreflective signs. Moreover, due to the retroreflective feature of microscale concave interfaces structures, the IR image showed a strong and stable pattern at different angles (Figure 13e). Overall, although still in the stage of early testing and development, the authors highlight that such technology shows potential for use in the field of road signs and optical sensing platforms, among others.

Figure 13 Visible and IR reflective road sign based on the microscale concave interfaces structures technology, under different light illumination conditions (Source: [69])

Another innovation was recently presented by the Dutch company HR Groep. It concerns self-illuminating road signs which include a foil similar to a mobile phone screen technology that illuminates the sign at night [70]. The sign uses sensors embedded in the foil, which automatically trigger the sign's illumination when the ambient light falls below a pre-set level. Moreover, the surface of the sign is created from a transparent layer of photovoltaic cells, which is a sort of a solar panel that enables the whole system to be self-powering. According to the company, due to the lack of external cabling and power sources, the self-illuminating signs can be retrofitted onto existing posts and provide sufficient light even in inclement weather conditions such as rain and fog. The sign should have a service life of at least 10 years according to HR Groep.

In 2018, Toh et al. presented another innovation by proposing that traditional road signs be replaced with wireless digital road signs [71]. In such a system, the digital road sign is a server capable of transmitting sign messages wirelessly to the driver's client device, which can be the car HUDs, car dashboard, ADAS display device, or a smartphone (Figure 14). Although the concept is relatively similar to RFID and radar technology, it should be analysed as a separate technology. In RFID or radar technology, RFID tags or radar systems are placed on the traditional road sign, while Toh et al. developed a new form of road signs which are completely different from the traditional ones. In comparison to RFID technology, wireless digital road signs are not limited by the short communication range and there is no need for good reader-to-tag alignment accuracy.

Figure 14 Programmable wireless digital traffic signpost architecture (Source: [71])

The main shortcoming of the system is that it may detect signals from the opposite lane on two-way roads. Authors see a solution for that in ADAS and its intelligent logic where software can filter the signals and thus process only those relevant for the specific travel direction and situation. Moreover, the authors emphasize that the main advantages of digital road signs are their proper functioning regardless of poor weather and lighting conditions, and their message flexibility, meaning that they can be easily reprogrammed if there is a specific need. Also, there is no need for complex signal processing and image recognition to recognise digital road signs in real time and the whole system including a wireless digital signpost is relatively inexpensive.

DIGITAL ROAD MARKINGS AND SIGNS

Vehicular communication is fundamental for the implementation and enhancement of cloud computing, cooperative driving, smart infrastructure and digital maps. In this chapter, the focus is on vehicular communication and digital maps which are representative of the advanced technologies used for the digitalisation of road infrastructure. As previously mentioned, vehicular communication has many sub-communication types, of which V2I and V2N are the most relevant for road infrastructure. They enable direct communication to infrastructure and clouds that are used to provide timely information to vehicles. Digital maps provide information about roads and lanes ahead that helps vehicles in localisation and to see beyond the sensor's field of view (FOV). Yet, to provide real-time updates of digital maps, vehicle communication is crucial.

5.1. Requirements

The introduction of higher automation levels gives rise to the demand for real-time information and high data transfer. It is not unusual to generate terabytes of data during a few hours of driving, which demands high computing power to collect and analyse data. Some of those storage demands could be cut down by using a lightweight digital map design. Such an approach is presented in [72] where the authors offered a localisation approach based on probabilistic models derived from the camera, LiDAR, GPS, IMU and wheel odometry. Detected signs and lanes are compared with lane graphs and traffic signs information extracted from HD maps. They manage to achieve median longitudinal precision of 1.12 m and lateral of 0.06 m while using a single GPU (NVIDIA GTX 1080) and have three orders of magnitude less storage than for 3D scan maps. Besides storage space, safety-critical functions require a data rate of at least 2.2 Gbit/s and maximum latency of 10 ms which is only possible with a 5G network [73]–[75]. However, it is necessary to stress that not all situations require such high demands. This means that in some situations safety-related ADAS systems should have priority over others. The 5G Automotive Association (5GAA) uses a requirement-based approach. This approach categorises ADAS regarding use-cases as safety-related, vehicle operation management, autonomous driving, platooning, traffic efficiency, and more [76], [77]. For each of the given use-cases, requirements like density, latency, data rate, and range are defined. This approach guides the prioritisation and selection of networks and thus can optimise the usage of V2X and network overloading. This may be crucial when dealing with a high penetration of vehicles equipped with such technology, which is necessary if we want to get the most out of vehicular communication and digital infrastructure. Network overloading concerns are especially addressed in short-range protocols like Dedicated Short-Range Communication (DSRC), Intelligent Transportation System (ITS-G5) and C-V2X, which offer sufficient range and latency with no more than 100 users/km^2 [78].

5.2. Maintenance

Road maintenance, monitoring all changes and updating the database of road infrastructure are some of the tasks of road authorities. Today's systems and human drivers do not demand urgent updates, however, the higher penetration of ADAS on the market and the introduction of digital maps will require changes to be updated in real-time. This means that all obstructions caused by vegetation or snow, as well as damages on the roadside, should be resolved in the shortest possible time.

It is hardly imaginable and not economically justified for those updates in databases or monitoring to be done by manual inspection, by road authorities, or map providers. Therefore, so-called crowdsourcing is a promising approach. It is a way of obtaining information from a large group of vehicles. Vehicles could provide information about construction works, queues, harsh road or weather conditions, and much more. This means that digital maps can be updated through public and private transport, which is often called the self-healing possibilities of maps. Records taken from the vehicles are updated to the cloud where data is further processed, checked on false positives and false negatives, and used to update the current state. In this way, the huge burden of costly and time-consuming manual monitoring and database updating process can be reduced. Map providers have announced that they are working on such solutions, one example including the collaboration between TomTom and Electrobit [79]. In recent years, many studies have been conducted to describe this solution (for more information see [80]–[82]).

5.3. Benefits, opportunities and challenges

According to the levels of automation introduced by SAE, automated driving is divided into support systems (up to SAE L2) in which human drivers are responsible for driving tasks, and into higher automation levels SAE L3 and L4 where the system takes care of fallbacks to a certain extent. Finally, complete automation with unlimited Operation Design Domain (ODD) is achieved with SAE L5. This means that a human-machine interface (HMI) is needed up to SAE L5, and through those levels, both human and machine perception should be considered. The introduction of ADAS should increase safety by preventing accidents caused by human drivers. Moreover, in the long term, ADAS should bring about higher efficiency and more comfort during the ride. Yet, during the transition period where both human drivers and machines are used to perform driving tasks, one concern arises. Studies show that driver drowsiness becomes more pronounced in the presence of ADAS [83], [84]. Therefore, it is of high importance to increase the reliability of ADAS, which is in any case necessary when moving towards SAE L2+. An increase in reliability can be viewed through functional safety and intended functionality perspective. ISO 26262 deals with functional safety by adequately reducing the risk that comes directly from system failures. On the other hand, ISO/PAS 21448 (SOTIF) is more focused on the functionality of the system, its potential misuse and situation awareness. Nevertheless, one way to reduce unreasonable risk and improve system performance in safety-critical situations is through software and hardware redundancy. In this sense, digital maps and vehicular communication offer road level system redundancy while on the vehicle level this can be done by sensor fusion. Therefore, digitalisation directly increases the reliability of the system through redundancy. This is beneficial in situations where the human driver is not fully aware of the situation or in managing control overtaking situations. Moreover, digital maps are a valuable addition to the vehicle's sensors. They provide map data far beyond the vehicle's sensor range. That helps to identify roads ahead and receive lane information even if sensors are blocked or under poor visibility due to weather conditions. This is the information that may be received via crowdsourcing.

The digitalisation of road infrastructure may reduce or even completely remove the necessity for certain activities. However, it would also open new jobs and business opportunities. Data science and AI algorithms are some of the fields that will be of huge importance in the future. With V2X a massive amount of data is collected and transferred across clouds. This enables obtaining new findings on vehicle behaviour, which could be used to optimise traffic or offer services to increase safety, comfort and efficiency. Those services could be smartphone applications, monetising data, voice-recognition-based services, personalization of driving experience, and many more [73].

Nevertheless, with data analysis and sharing comes responsibility for the accuracy of information. The liability for provided data has not yet been solved. Data sharing also entails several more challenges. Data has a huge value, and data collected in the vehicle and used by the OEM cloud is subject to confidentiality. Yet, in order to achieve higher levels of automation, cooperation models between different entities included in traffic control will play a significant role [85]. Adding more ADAS features to vehicles means higher computing demands. Switching to cloud computing may get the most out of collected data and at the same time reduce requirements on vehicles themselves [73], [86]. However, high sharing demands and network access result in higher security demands [87], [88]. In this respect, blockchain security-related technology shows promising results [89], [90].

5.4. Vehicular communication

Vehicular communication is a network in which vehicles, roadside units (RSU) and pedestrians are communication nodes. As previously mentioned, in general terms, direct communication is defined as vehicle-to-everything (V2X). It is further divided into specific communication types such as vehicle-to-pedestrian (V2P), vehicle-to-network (V2N), vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and more (Figure 15). When we talk about AV in terms of connectivity, often the term connected automated vehicles (CAV) is used.

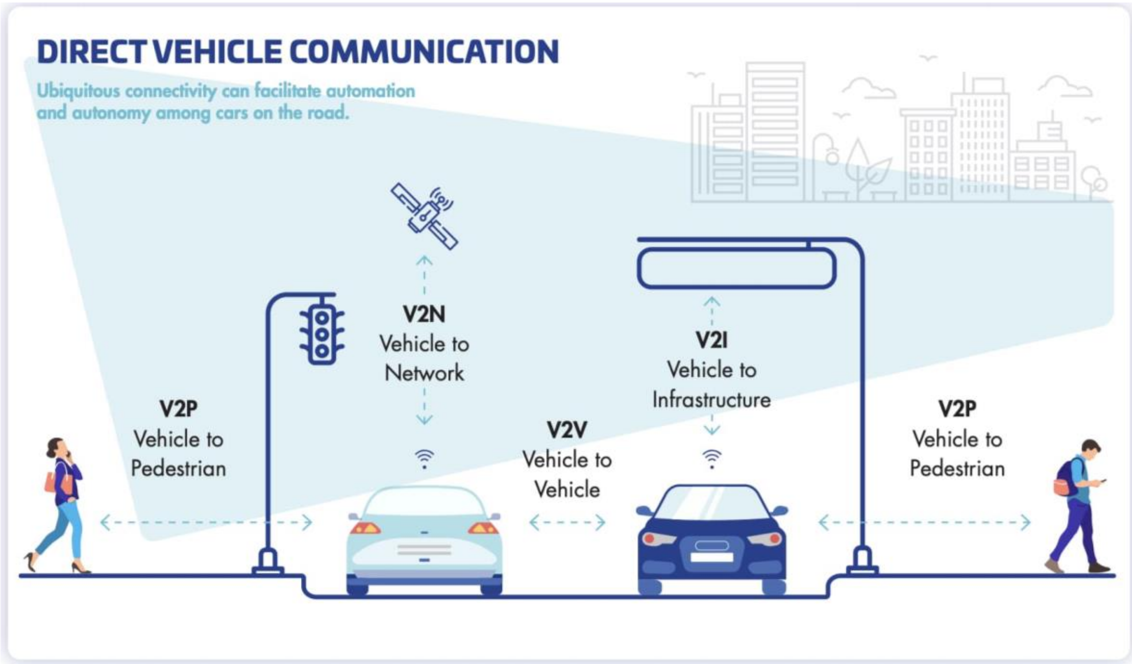


Figure 15 Vehicle-to-everything (V2X) (Source: [91])

Vehicular communication is one of the approaches used to digitalise road infrastructure. Similar to other trends, its tasks are the following:

- Enable the vehicle to see beyond the range of its onboard sensors (see Figure 16);
- Receive and send information in real-time from other communication nodes about the road ahead and its state;
- Operate in all-weather conditions;
- Increase reliability of AD by supporting and adding redundancy to onboard sensors.

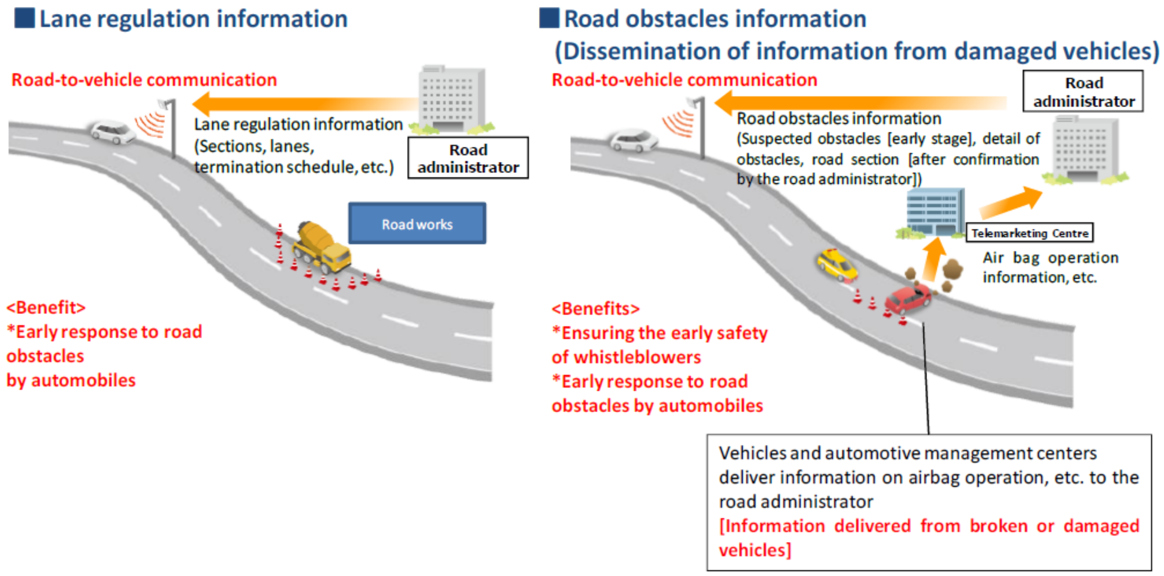


Figure 16 Service for providing information on the road ahead (Source: [85])

Timely information about the road ahead such as working zones, ice, accidents, and more is of huge importance for safety. In addition to safety, synchronisation with traffic infrastructure, such as traffic lights, also improves comfort and fuel efficiency. To cope with those challenges, several communication protocols have been introduced. We can divide them into short-range and long-range.

Intelligent Transportation System (ITS-G5) and Dedicated Short-Range Communication (DSRC) are two vehicular communication protocols that use the allocated 5.9 GHz spectrum band. Both are based on the IEEE 802.11p physical layer that adds wireless access in vehicular environments (WAVE) to the IEEE 802.11 standard for wireless local area network (WLAN) used in most home and office networks [78]. ITS-G5 is a protocol developed by the European Telecommunications Standards Institutes (ETSI), while DSRC has been developed in the US. Those protocols can deal with short to medium ranges typically up to 300m, at which they show sufficient latency for ADAS (10ms) if they are not overloaded (100users/km2); more is possible but with increased latency [78]. The benefit of those systems is that they work in any environmental conditions and areas without telecommunication infrastructure as they do not depend on the cellular network. A competitive system C-V2X, offered by the 3rd Generation Partnership Project (3GPP), shows improvements over ITS-G5 and DSRC, especially for user density and usage of cellular network, which make it a more flexible technology. Such technology offers not only direct communication like V2V or V2I, but also an indirect one such as V2N, which is not covered by ITS-G5 and DSRC [74]. Moreover, in later releases, 3GPP added compatibility to 5G and 5G NR. Those are normally reasons that show an increase in popularity. However, ITS-G5 and DSRC are more mature and already commercialised and this is a slight advantage over C-V2X for the time being.

Cellular technology like 5G offers higher bandwidth, data rate up to 4.5 Gbit/s, wider coverage up to 2000m, and low latency < 1ms, therefore, it is a promising candidate for V2X communication. 5G is still not in wide and commercial use but rather limited to the research. However, popularity is already noticeable as AUDI AG, BMW Group, Daimler AG, Ericsson, Huawei, Intel, Nokia and Qualcomm Incorporated started 5GAA with the idea to connect telecommunication and car manufacturers. Currently, there are more than 130 automotive manufacturers, tier-1 suppliers, chipset/communication system providers, mobile operators and infrastructure vendors that joined the association.

Vehicular communication is still facing some challenges: the "alignment challenge", the technology challenge, and also data and security challenges. First, to make things happen and for V2X to work smoothly, all actors involved (manufacturers, public transport providers, transport authorities) need to align and collaborate.

The "technology challenge" regarding C-V2X and ITS-G5/DSRC protocols has been mentioned above. Today, there are still no regulations, so manufacturers will have to deal with both technologies in the years to come.

Even if V2X is really promising, this kind of technology requires and generates a huge amount of data that could be difficult to manage. Artificial Intelligence (AI) data processing solutions are already in use in the industry or for logistics operations and should be extended to the management of big data in vehicular communication.

Finally, there is a considerable security challenge. Lack of security and a cybersecurity adversary could have dramatic effects when dealing with human lives. It is necessary to define a common standard for data sharing and security for all actors involved.

5.4.1. Market solutions & applications

The first V2I service, the Traffic Light Information (TLI), was offered by Audi in 2016 in Las Vegas [92]. The service provided timely information about the traffic light state and sent data to the vehicle via 4G/LTE. Information received from the traffic light is used to inform the driver about the red-light phase duration and recommended speed to hit the green light (Figure 17).

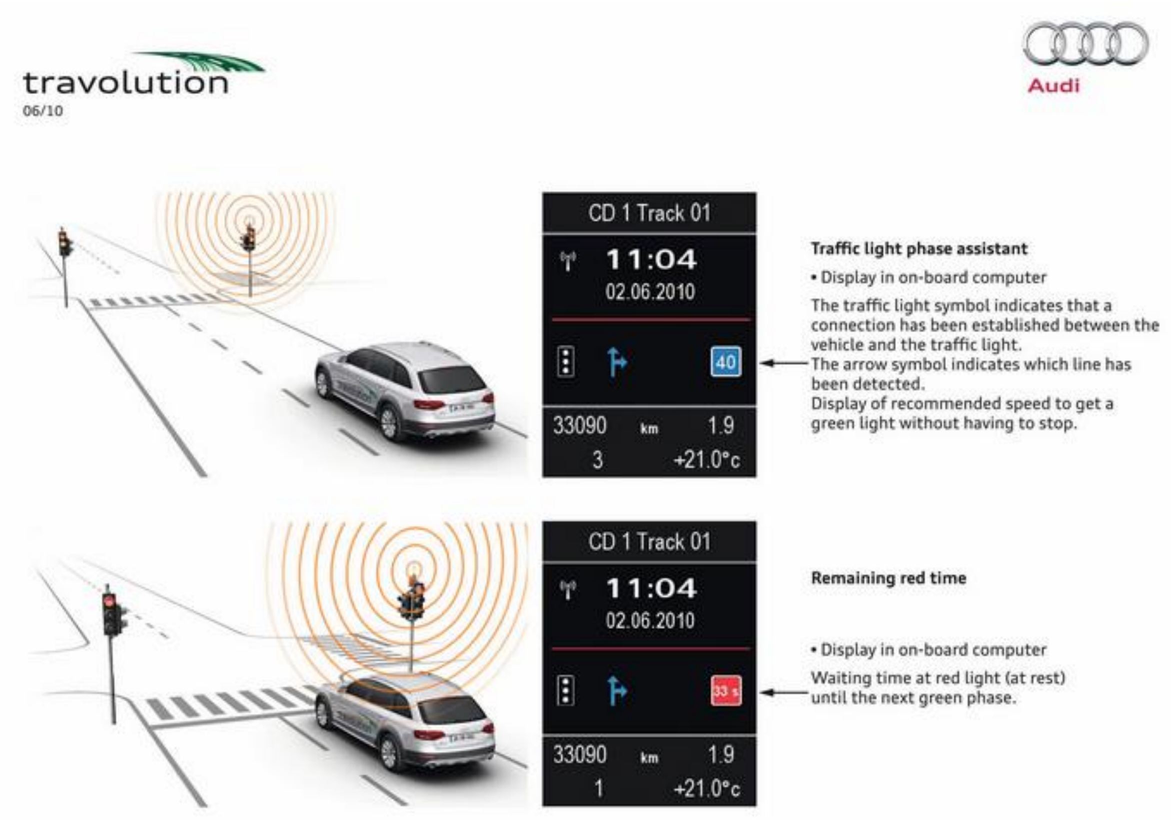


Figure 17 TLI operation (Source: [93])

This service offers several benefits, namely by reducing unpredictable situations which contributes to safety, improving traffic flow which increases driving comfort and decreasing the number of stop-and-go events which increases fuel efficiency. Today the system is available in more than 10,000 intersections in North America, Ingolstadt and Dusseldorf. In the future, the technology will switch to 5G and C-V2X and expand to more cities around the globe. However, TLI's ability is not limited to informing the driver about the current situation but it also informs road authorities and companies that deal with data analysis. They can use this information to optimise duration phases of the traffic light state and thus improve traffic flow and fuel efficiency.

Smart parking is another system that exchanges information between infrastructure and vehicles. Yet, this is not often managed through direct communication like V2I or V2N. Current systems use road infrastructure to place radars or cameras which observe parking places and the information received from sensors is processed and sent via mobile applications to drivers. Such examples of smart parking are available in San Francisco, Singapore, Berlin, and many others [94]. More advanced smart parking solutions based on V2V and V2I are currently more limited to research [95], [96].

In addition to examples that solve particular aspects of traffic like TLI or parking, the application of vehicular communication, in general, may include many parties and complex information flow. One such example is Volvo Drive-Me [97]. This is a project that defines and proposes a cloud-based traffic control and information sharing that involves CAV of higher automation levels, road authorities, city authorities, telecommunication companies, and others. The project ended in June 2017, it was partly financed by Vinnova, Sweden's innovation agency, and included Volvo Cars, Ericsson, Carmenta, Trafikverket, and the City of Gothenburg. Figure 18 shows the system architecture of traffic control in this project. The central part of the system is the so-called Central Traffic Control (CTC) Cloud which is intended as a public or a public-private partnership. The CTC is used to exchange information between OEM's cloud and other parties like weather data providers or road authorities. OEM's clouds are responsible for AD functionalities as they are aware of vehicle capabilities. Information on the road collected with CAVs is sent to CTC which forwards it to road authorities for situation awareness. Road blockages, lane closures, work zones, the weather ahead, and other road and weather-related information are sent from road authorities and weather provider clouds through CTC to OEM clouds and vehicles.

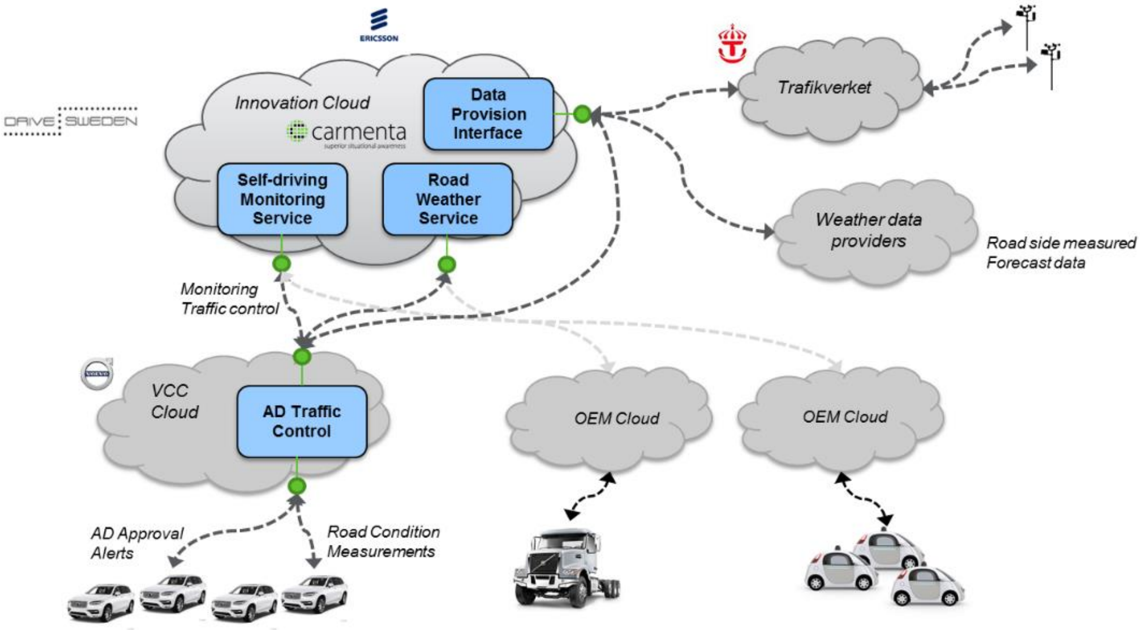


Figure 18 System architecture of Drive-Me (Source: [97])

5.5. Digital Maps

Navigation maps have been widely used over the past decades. Those maps rely on a global navigation satellite system (GNSS) and combine geospatial and electronic information. GNSS is based on triangulation from different satellites to determine the position of the receiver. This approach is sufficient to support human drivers in navigation and perform useful features like calculation of the fastest route or avoiding tolls.

Yet, the development of ADAS increased the demands on maps. The so-called digital maps have been introduced. They are based on the geographical information systems (GIS), the layered map representation where each layer is dedicated to a certain information type. The background layer is normally called a basic map and provides location references that do not change often. They can be obtained from state and national organisations and further enhanced with additional context. Digital maps are in principle layers that hold information about signs, landmarks, road curvatures, slopes, speed, road rules, or on higher levels lane information, road conditions, traffic congestion, and more. The latter features are intended for higher levels of automation, and they are the so-called high-definition (HD) maps (Figure 19).

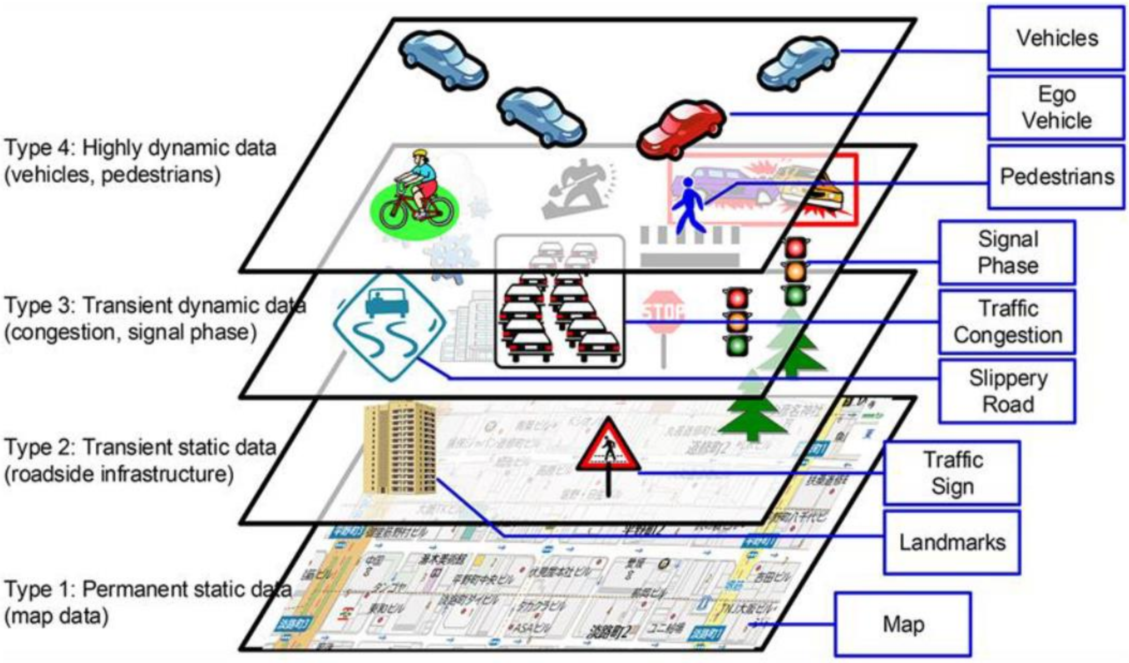


Figure 19 The four-layer local dynamic map model proposed in Shimada et al. (Source: [98])

Digital maps are intended to support ADAS by providing a view beyond onboard sensors' FOV and offer redundant systems which are consistent with the safety culture promoted through functional safety. For systems up to SAE L2, it is sufficient that digital maps contain road information as systems require road-level accuracy of several meters. However, higher levels of automation require a centimetre precision, which is why HD maps are needed. The benefits of the centimetre-precise maps for AV are multiple and can support tasks like localisation, environment perception and path planning [99], as presented in Table 1.

Table 1 Three main fields of digital maps applications (Source: [99])

Task	Description
Localisation	An automated vehicle must be able to precisely determine its position in regard to other static and dynamic objects. An HD map in correlation with sensory infomation can help in centimetre-precision longitudinal and lateral position predictions which help ADAS to adjust its distance from
Environment perception	The vehicle perceives its environment with sensors like cameras or LiDARs. However, due to view blockage, harsh weather or light conditions it may be hard to detect objects or to identify the environment in its right context. In that case, HD maps bring detailed information about road geometry regardless of environmental conditions and beyond sensors' view range.
Path planning	For reasons similar to those stated above, with the help of HD maps vehicles can improve path planning as they provide a longer horizon and precise object positions.

Besides the mentioned benefits, digital maps would be "self-healing", meaning they would be updated using vehicle sensors, which satisfy a real-time requirement for automated vehicles and reduce the need for map updates currently done by map providers and road authorities.

5.5.1. Market solutions & applications

Commercial availability of digital maps is still limited as they are not needed at a large scale and are rather expensive to be developed without an existing demand. With higher penetration of automated vehicles (AV), the need for digital maps will increase [100]. Normally, digital maps are developed by companies dealing with localisation and mapping like TomTom or HERE, which, in recent years, caught the attention of vehicle manufacturers and their suppliers regarding the development of AVs and CAVs [101].

The production of digital maps starts with road scans, collected with specially equipped vehicles, which are then converted to HD maps and stored in map provider and OEM clouds. Maps are delivered to vehicles by streaming directly or downloading to the vehicle's cloud or via Navigation Data Standard (NDS) format. To make the map readable by different distributors and ready for different systems and OEMs, there is a standardised protocol and interface called Advanced Driver Assistance Systems Interface Specification (ADASIS) which is maintained by the ADASIS forum, a non-profit international organisation. In 2018 ADASIS v3 protocol was released which has lane-level accuracy and is intended for handling HD maps, therefore, SAE Level 2+.

To support the AD, TomTom offers so-called ADAS and HD maps which differ in levels of detail and are therefore used for different SAE levels of automation [102]. As stated by TomTom, ADAS maps reach their limitation already at Level 2. For ADAS above Level 2, more precise HD maps are needed. Maps can come standalone or as part of the navigation map. They are created in layers that allow customers to adopt map information to their needs, therefore if an HD map is not required, only an ADAS map can be streamed. Connected cars themselves update the maps by sending perception sensor information back to the cloud where they are combined with various other sources. Since 2017 TomTom and Electrobit have jointly been offering up-to-date map-based solutions based on ADASIS v2 and ADASIS v3 [79].

HERE delivers maps through three layers Road Model, HD Lane Model, and HD Localization Model [103]. Road Model contains road topology curvature and speed limits, so in more general terms, the road-level information. HD Lane Model is lane level that offers more precise information containing lane geometry, marking types, and more. HD localisation adds objects like signs, guardrails, and barriers to help localisation of vehicles within centimetre precision.

Some of the ADAS that use digital maps are Intelligent Speed Assistance (ISA), also in combination with ACC, and predictive powertrain control (PPC), as presented in Table 2.

Table 2 ADAS that are combined or could be combined with digital maps to improve their functionality

ADAS	Description
Intelligent Speed Assistance (ISA)	ISA informs drivers of the road speed limits and, if necessary, automatically reduces vehicle speed [104]. As of 2022, EU legislation made ISA mandatory for all new vehicles and all existing per 2024 [103]. Digital maps are used in this application as a supplementary system that sees beyond the onboard camera range and in all weather conditions.
Predictive Powertrain Control (PPC)	PPC receives road topology, curvature, traffic signs and speed limits from digital maps (Figure 20). Therefore, it can determine a safe and efficient speed and a slow-down/speed-up strategy for the upcoming road. The system reduces collisions by up to 20% and fuel consumption by around 5% [106]. The system is currently used in Mercedes-Benz Actros [107].
Cooperative Adaptive Cruise Control (CACC)	ACC is well known and rather an "old" ADAS but supported with digital maps it opens new horizons. CACC is an advanced adaptation of classical ACC. It incorporates data from GNSS, digital maps and V2V communication to support systems and human drivers on obstructed roads like tight corners or hilly roads [108], [109].
Lane Keeping Assist (LKA)	LKA is a well-established ADAS that could increase its functionality and reliability in adverse weather conditions when combined with digital infrastructure. Studies [110]–[112] show potential for improvement of LKA by enhancing them with digital infrastructure.

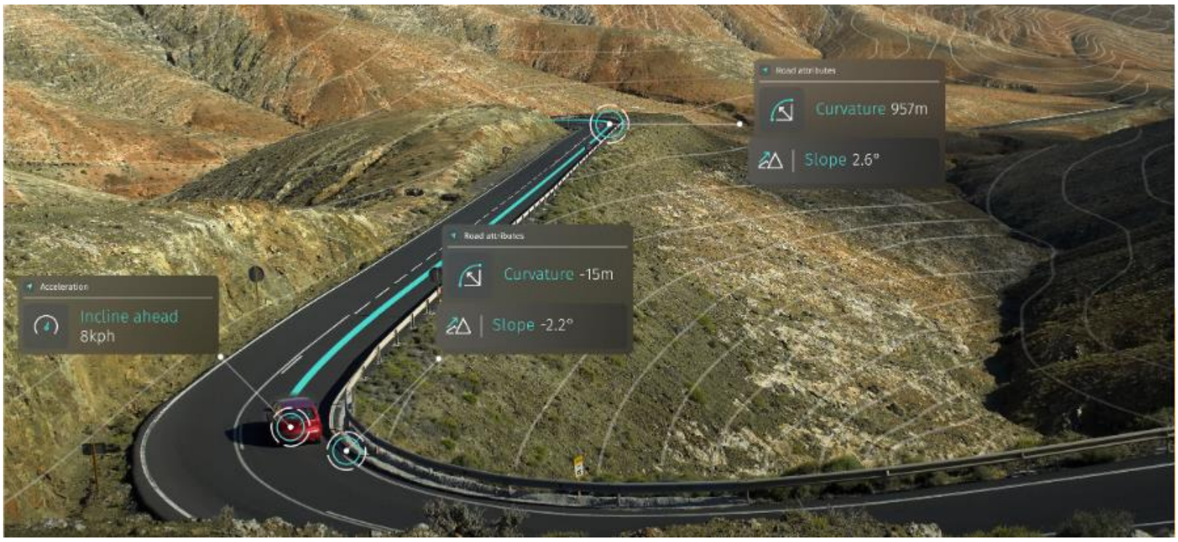


Figure 20 Different road information that PPC receives (Source: [103])

5.5.2. Digital maps of road markings and road signs – EU examples

Although the importance and necessity of digital maps is growing, in the EU only a few countries have such databases for road markings and road signs. In 2016, Croatian Roads Ltd., a company that manages state roads in Croatia (road category below motorways), started a project to develop a digital database of road signs. The road network included in the project was approximately 7,000 km long. During the project, the following information was collected for each road sign located on the state road network [113]: a) number of the state road and road section; b) position of the sign; c) GPS coordinate of the sign; d) ID of the sign according to the legislation; e) direction of the sign; f) class of retroreflective material; g) retroreflection values for each colour on the sign; i) dimensions; j) shape of the sign; k) sign manufacturer; l) year of manufacture; m) height of the sign; n) distance from the edge of the roadway; and o) photo of the sign.

After establishing the database, the second part of the project aimed to develop an automatic system for controlling and updating the database. As stated in Section 4.3., after conducting pilot tests, as of 2020 Croatian Roads Ltd. has started to implement passive RFID tags on every road sign in the aforementioned state road network. The configuration of the system is presented in Figure 21. Until today, approximately 80,000 RFID tags have been placed on road signs on the network of 3,750 km of state roads across Croatia.

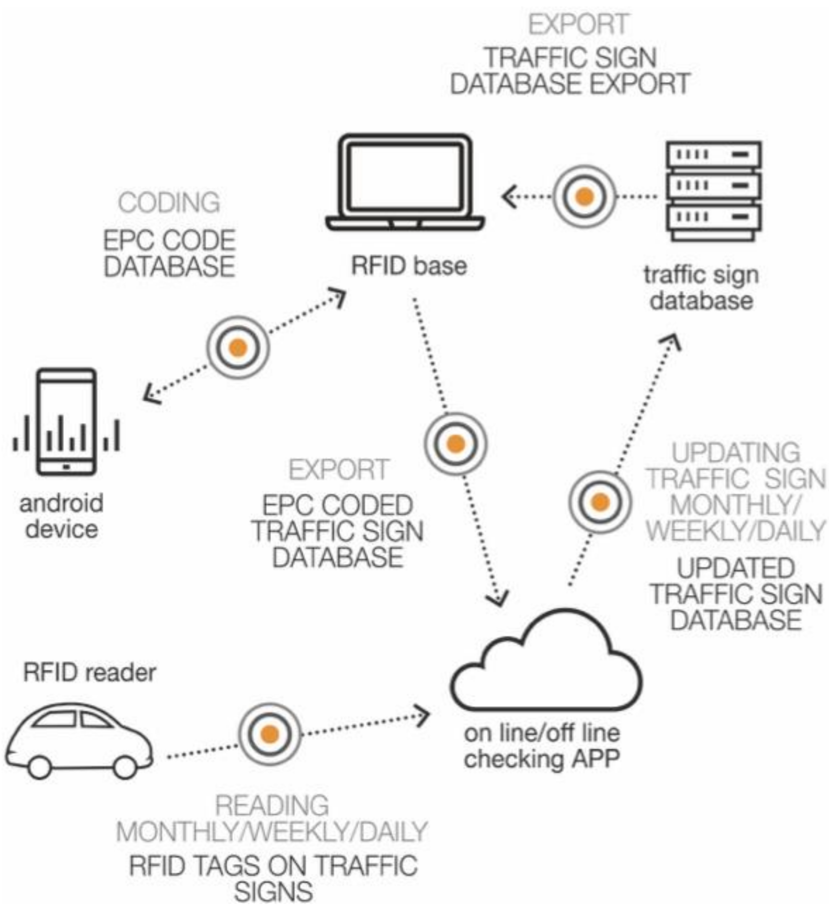


Figure 21 Configuration of the system for automatic road sign database update using RFID technology in Croatia (Source: [113])

Moreover, in 2018 Croatian Roads Ltd. continued expanding the database with road markings. The data relating to the type of the marking, colour, material from which the marking was implemented, last application date, width and length of the marking, position of the marking and GPS location were collected and entered into the database.

The main purpose of this database is to achieve a more efficient road asset management. In other words, the database is used by road authorities (Croatian Roads Ltd.) for planning and optimising maintenance activities for road markings and road signs.

In 2020, the Netherlands became the first country in the world to create an open digital database of road signs on all national roads [114]. The project was commissioned by the Ministry of Infrastructure and Water Management and the regional authorities, and it included collecting the image on the sign, the indication code, and the exact location of the sign, for each road sign in the Netherlands. As stated, the database is available via the National Data Warehouse for Traffic Information (NDW) as open data and is used by information service providers and road authorities. Moreover, the Netherlands passed a law prescribing that after the physical implementation of a road sign on the national road, the sign must be also implemented into the existing database (digital twin). The control and update of the sign in-place are done with inspection vehicles equipped with machine vision which detects and recognises the signs.

The main purpose of the database is to help road authorities to manage and maintain road signs more efficiently and to provide information to information service providers and suppliers of navigation equipment in order to enable optimum information provision to road users: on current speed limits, parking facilities, or loading and unloading bays, but also on overtaking prohibitions, narrowing etc. [114]. By providing an accurate road sign database to different stakeholders, the Dutch government aims to boost overall road safety.

6. CONCLUSION

Traditionally, the main task of road markings and road signs, as one of the fundamental elements of road infrastructure, was to provide timely and necessary information about the upcoming situation to human drivers. However, with the development of vehicle safety systems, road markings and road signs have become a valuable source of information for certain ADAS technologies as well.

During the last decade, a significant amount of research interest focused on road markings and road signs and their development. The main driving forces of these research activities are the increase in road safety awareness and the implementation of contemporary road safety strategies which seek to improve the road infrastructure in order to facilitate the needs of all drivers, as well as the needs of evolving vehicle technologies.

The main aim of this work package (WP4) of the "Study on common specifications for road markings and road signs" is to identify and analyse ongoing innovation and research activities related to road markings, road signs and ADAS technologies based on literature research and consultation with relevant stakeholders active in the aforementioned fields. Moreover, the objective of this work is to identify the trends which may lead to the improvement of detectability and readability of road markings and road signs in the future.

When it comes to ADAS, several technologies such as vehicular communication, digital maps, smart infrastructure, cloud computing, cooperative driving and sensor fusion are analysed. In terms of improving the detectability and readability of road markings and road signs, technologies such as sensor fusion, digital maps and vehicle-to-infrastructure and vice versa communication (V2I/I2V) show the highest potential. Due to the limitations in the use of current sensors in vehicles, the aforementioned technologies should provide additional information and redundancy to ADAS and thus improve the overall accuracy of detection and readability of road markings and road signs. Specifically, sensor fusion enhances the performance of perception through inputs from multiple radars, LiDAR and cameras. Digital maps are the "digital twins" of physical infrastructure and contain information about the road ahead, traffic conditions, speed limits, road signs and road markings etc., while V2I and I2V communication could provide additional information utilizing different road infrastructure elements to specific vehicular safety systems.

On the other hand, innovations and new technologies related to road markings and road signs mainly focus on improving their quality in terms of visibility and durability by enhancing and developing new materials for their application. It is expected that further enhancement of materials for road markings and road signs will be the main trend in the coming years that will bring the most benefits in terms of improving their detectability and readability by both human drivers and ADAS. Moreover, it is expected that further improvements in uniformity and standardisation of road markings and road signs will also bring benefits in terms of their detectability and readability, especially by ADAS. Ongoing work from the UNECE Global Forum for Road Traffic Safety (WP.1) and their expert group identified several inconsistencies and inaccuracies in the Convention on Road Signs and Signals, and it is expected that proposed amendments, together with the development of the electronic version of the Convention (e-CoRSS), would lead to easier interpretation and more effective implementation of the Convention.

Besides the aforementioned, several other innovations and new technologies, which show potential in terms of improving the detectability and readability of road markings and road signs as well as infrastructure-to-vehicle communication, have been identified in this report. These innovations mainly include the use of RFID, radar or QR technology to develop the so-called "smart road signs and road markings". Although initial research activities show promising potential and a relatively low cost of such technologies, more testing is needed to evaluate their full potential and to determine the limitations and cost aspects of their implementation.

Other innovations, such as luminescent road markings, wireless digital road signs or retroreflective structural colour films technology for road signs are also interesting ideas. However, due to the very limited knowledge currently available, it is not expected that such technologies will be used in the near future.

Overall, based on literature review and consultations with relevant stakeholders active in the field, a summary of the findings and likelihood of identified innovations, new technologies and trends on the improvement potential of detectability and readability of road markings and road signs in the future, are presented in Table 3.

Table 3 Summary of main innovations, technologies and trends in the field of ADAS technologies, road markings and road signs

Innovation / technology	Area	Benefits	Limitations	Likelihood of application in the near future
Sensor fusion	Vehicle/ADAS	- Enhanced performance of vehicle perception through inputs from multiple sensors (radars, LiDAR and cameras) - Increases reliability of ADAS by information redundancy	- Potential higher costs - Lack of standardisation - Technical difficulties due to alignment of multimodal data coming from different sensor units	High
Digital maps	Vehicle/ADAS	- In correlation with the vehicle's sensors suite offers localisation with centimetre precision - Perceiving environment beyond sensor's field of view - Accurate path planning with real-time updates on road conditions and traffic ahead	- Potential high costs of developing and maintaining such maps - Liability for provided data - Security and privacy - Highly dependable on the penetration of ADAS on the market	High
V2I/I2V communication	Vehicle/ADAS	- Provides vehicles with additional information about the upcoming road situation - Real-time updates via crowdsourcing - Potentially can be used to optimise traffic flow and energy efficiency	- Relatively high initial costs - Technical specification for safety-critical and high-capacity application only achievable with 5G communication	High

Enhancements in the materials	Road markings / road signs	- Improved visibility, especially during low visibility conditions - Improved durability - Potential optimisation of costs during a longer period due to improved durability	- Higher initial application costs - May not have desired cost-benefit effect on all roads and in all climate regions	High
Uniformity and standardisation	Road markings / road signs	- Improved detectability and readability of road markings and road signs, especially by ADAS	- Different standards among countries - Relatively long period of adjustment to new standards - Potential higher costs of adjusting to new standards	High
Self-illuminating road signs	Road signs	- Higher visibility during night-time and diverse weather conditions - Self-powering technology - Technology can be retrofitted onto existing signs - Service life similar to standard retroreflective materials (according to the technology developer)	- Higher costs compared to standard retroreflective materials - Unknown impact on detectability and readability of road markings by machine-vision	Medium
RFID technology	Road signs	- Higher accuracy of road signs detection by ADAS, under diverse weather conditions - Redundancy to the standard sensors used for detection of road signs - Relatively low cost, simple and well-known technology - May provide benefits to road authorities in terms of optimisation of maintenance activities and road sign inventory updates	- Potential problems related to the interference between RFID tag and metal plate from which sign is produced - Reduced detection at higher driving speeds and with the increase of the distance from RFID reader and sign (different positions of the sign) - Durability of RFID tags - Costs and efficiency of the system may vary depending on the type of the tag (passive vs active)	Medium

QR codes	Road signs	- Higher accuracy of road signs detection by ADAS during daytime and night-time - Redundancy to standard sensors used for detection of road signs	- Higher costs of road sign production - Potential problems with the reading distance, error correction and reading confidence - Unknown efficiency in diverse weather conditions (rain, fog etc.) - Unknown durability and impact on the retroreflectivity of the sign - Lack of more real road tests	Medium
Radar technology	Road signs	- Higher accuracy of road signs detection by ADAS, under diverse weather conditions - The technology may enable V2I/I2V communication	- Higher costs of sign production (implementation of built-in radar system) - Unknown durability of the system - Lack of more real road tests	Medium
RFID technology	Road markings	- Higher accuracy of road markings detection by ADAS - Redundancy to standard sensors used for detection of road markings - Relatively low cost, simple and well-known technology	- Potentially may impact the complexity of road markings application, and thus application costs - Lack of more real road tests - Unknown durability and effectiveness over a longer period	Low
Luminescent road markings	Road markings	- No need for the use of standard road marking materials and glass beads	- Low visibility in wet and rainy conditions - Higher application cost and lower durability compared to standard materials - Unknown impact on driver behaviour and on detectability and readability of road markings by machine-vision	Low

Retroreflective structural color films	Road signs	- Dynamically changing colours on the sign which may be beneficial for increasing road safety during night-time	- Unknown costs and durability of the material - Unknown visibility during diverse weather conditions - Unknown impact on driver behaviour and on detectability and readability of road markings by machine-vision - Lack of more real road tests	Low

REFERENCES

[1] S. Ricketts, "What's Next for Advanced Driver Assistance Systems (ADAS) Technology?" https://www.jabil.com/blog/advanced-driver-assistance-systems-future.html (accessed Dec. 21, 2021).

[2] C. Jones and S. Fitzpatrick, "Huge opportunity as only 10% of the 1 billion cars in use have ADAS features." https://www.canalys.com/newsroom/huge-opportunity-as-only-10-of-the-1-billion-cars-in-use-have-adas-features (accessed Dec. 22, 2021).

[3] Canalys, "Level 2 autonomous driving Q4 2020 and full year 2020." https://www.canalys.com/newsroom/canalys-autonomous-driving-starts-to-hit-mainstream-as-35-million-new-cars-had-level-2-features-in-q4-2020 (accessed Dec. 22, 2021).

[4] Markets and Markets, "ADAS Market Analysis." https://www.marketsandmarkets.com/Market-Reports/driver-assistance-systems-market-1201.html (accessed Dec. 21, 2021).

[5] K. Shirokinskiy, Bernhart Wolfgang, and S. Keese, "Advanced Driver-Assistance Systems: A ubiquitous technology for the future of vehicles." https://www.rolandberger.com/en/Insights/Publications/Advanced-Driver-Assistance-Systems-A-ubiquitous-technology-for-the-future-of.html (accessed Dec. 22, 2021).

[6] Technavio, "Automotive ADAS Sensors Market by Product and Geography - Forecast and Analysis 2021-2025." https://www.technavio.com/report/automotive-adas-sensors-market-industry-analysis (accessed Dec. 22, 2021).

[7] Mordor Intelligence, "Sensor fusion market in autonomous vehicles - growth, trends, COVID-19 impact, and forecasts (2022 - 2027)." https://www.mordorintelligence.com/industry-reports/sensor-fusion-market-in-autonomous-vehicle (accessed Dec. 22, 2021).

[8] Fatpos Global, "V2X Market." https://www.marketresearch.com/Fatpos-Global-v4217/Automotive-Vehicle-Everything-V2X-Connectivity-30794839/ (accessed Dec. 22, 2021).

[9] Cognitive Market Research, "Global HD Maps Market Report 2022 ," 2021. Accessed: Dec. 22, 2021. [Online]. Available: https://www.cognitivemarketresearch.com/hd-maps-market-report

[10] Infogence Global Research, "Global HD Map for Autonomous Vehicles Market (2021-2027) by solution, level of automation, usage, vehicle type, services, and Geography, IGR Competitive Analysis, Impact of Covid-19," 2021. Accessed: Dec. 22, 2021. [Online]. Available: https://www.researchandmarkets.com/reports/5451194/global-hd-map-for-autonomous-vehicles-market

[11] P. Jing, G. Xu, Y. Chen, Y. Shi, and F. Zhan, "The Determinants behind the Acceptance of Autonomous Vehicles: A Systematic Review," *Sustainability*, vol. 12, no. 5, p. 1719, Feb. 2020, doi: 10.3390/su12051719.

[12] D. Babić, T. E. Burghardt, and D. Babić, "Application and Characteristics of Waterborne Road Marking Paint," *International Journal for Traffic and Transport Engineering*, vol. 5, no. 2, pp. 150–169, Jun. 2015, doi: 10.7708/ijtte.2015.5(2).06.

[13] M. Taheri, M. jahanfar, and K. ogino, "Self-cleaning traffic marking paint," *Surfaces and Interfaces*, vol. 9, pp. 13–20, Dec. 2017, doi: 10.1016/j.surfin.2017.07.004.

[14] R. J. Benz, A. M. Pike, S. P. Kuchangi, and Q. Brackett, "Servicable pavement marking retroreflectivity levels," Austin, Texas, USA, 2009. Accessed: Dec. 16, 2021. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/16849

[15] T. E. Burghardt, D. Babić, and D. Babić, "Application of Waterborne Road Marking Paint in Croatia: Two Years of Road Exposure," in *International Conference on Traffic and Transport Engineering (ICTTE)*, 2016, pp. 1092–1096.

[16] T. E. Burghardt and A. Pashkevich, "Green Public Procurement criteria for road marking materials from insiders' perspective," *Journal of Cleaner Production*, vol. 298, p. 126521, May 2021, doi: 10.1016/j.jclepro.2021.126521.

[17] D. M. Burns, T. P. Hedblom, and T. W. Miller, "Modern Pavement Marking Systems," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2056, no. 1, pp. 43–51, Jan. 2008, doi: 10.3141/2056-06.

[18] T. E. Burghardt and A. Pashkevich, "Materials selection for structured horizontal road markings: financial and environmental case studies," *European Transport Research Review*, vol. 12, no. 1, p. 11, Dec. 2020, doi: 10.1186/s12544-020-0397-x.

[19] J. Hatfield, S. Murphy, R. F. S. Job, and W. Du, "The effectiveness of audio-tactile lane-marking in reducing various types of crash: A review of evidence, template for evaluation, and preliminary findings from Australia," *Accident Analysis & Prevention*, vol. 41, no. 3, pp. 365–379, May 2009, doi: 10.1016/j.aap.2008.12.003.

[20] A. Gail and W. Bartolomaeus, "Noise Emission of Structured Road Markings," *Procedia - Social and Behavioral Sciences*, vol. 48, pp. 544–552, 2012, doi: 10.1016/j.sbspro.2012.06.1033.

[21] E. S. Park, P. J. Carlson, and A. Pike, "Safety effects of wet-weather pavement markings," *Accident Analysis & Prevention*, vol. 133, p. 105271, Dec. 2019, doi: 10.1016/j.aap.2019.105271.

[22] A. Pike, S. Clear, T. Barrette, T. Hedblom, and J. Whitney, "Effects of the Wet Retroreflectivity and Luminance of Pavement Markings on Lane Departure Warning in Nighttime Continuous Rain with and without Glare Sources," Apr. 2019. doi: 10.4271/2019-01-1014.

[23] C. Lyon, B. Persaud, and K. Eccles, "Safety Evaluation of Wet-Reflective Pavement Markings," Washington, DC, USA, 2015. Accessed: Dec. 17, 2021. [Online]. Available: https://www.fhwa.dot.gov/publications/research/safety/15065/15065.pdf

[24] A. M. Pike, J. Whitney, T. Hedblom, and S. Clear, "How Might Wet Retroreflective Pavement Markings Enable More Robust Machine Vision?," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2673, no. 11, pp. 361–366, Nov. 2019, doi: 10.1177/0361198119847620.

[25] A. R. Abbas, P. Sarker, and A. Frankhouser, "Performance Evaluation of Wet Pavement Markings in Ohio," *Public Works Management & Policy*, vol. 19, no. 2, pp. 180–197, Apr. 2014, doi: 10.1177/1087724X13500944.

[26] N. R. Hawkins, A. M. Pike, O. G. Smadi, S. Knickerbocker, and P. J. Carlson, "Evaluating All-Weather Pavement Markings in Illinois: Volume 1," Springfield, IL,

USA, 2015. Accessed: Dec. 17, 2021. [Online]. Available: https://intrans.iastate.edu/app/uploads/2015/12/FHWA-ICT-15-018.pdf

[27] T. E. Burghardt, A. Pashkevich, D. Babić, H. Mosböck, D. Babić, and L. Żakowska, "Microplastics and road markings: the role of glass beads and loss estimation," *Transportation Research Part D: Transport and Environment*, vol. 102, p. 103123, Jan. 2022, doi: 10.1016/j.trd.2021.103123.

[28] European Committee for Standardization, "European Standard EN 1423:2012/AC:2013. Road marking materials. Drop on materials. Glass beads, antiskid aggregates and mixtures of the two." European Committee for Standardization, Brussels, Belgium, 2012.

[29] S. Y. Shin, J. I. Lee, W. J. Chung, and Y. G. Choi, "Correlations between Refractive Index and Retroreflectance of Glass Beads for Use in Road-marking Applications under Wet Conditions," *Current Optics and Photonics*, vol. 3, no. 5, pp. 423–428, 2019.

[30] T. E. Burghardt, A. Pashkevich, and J. Bartusiak, "Solution For a Two-Year Renewal Cycle of Structured Road Markings," *Roads and Bridges-Drogi i Mosty*, vol. 20, no. 1, pp. 5–18, 2021.

[31] T. E. Burghardt, A. Pashkevich, and K. M. Wenzel, "A Study of Premium Glass Beads for Road Marking Materials," *Roads and Bridges-Drogi i Mosty*, vol. 20, no. 2, pp. 125–138, 2021.

[32] Texas Transportation Institute and Virginia Tech Transportation Institute, "Markings with Embedded Sensors," 2017. https://cote.transportation.org/wp-content/uploads/sites/26/2017/07/Embedded-Sensor-Markings-VDOT.pdf (accessed Jan. 02, 2022).

[33] S. Capato, L. Coconea, B. Helmreich, T. Kreckel, and M. Gkemou, "Intelligent Road Marking Systems enabling future connected mobility," 2018.

[34] N. Fritz, M. Kamps, H. Harald Widlroither, and J. P. Leuteritz, "Safe Strip deliverable D7.7: Application guidelines and standardisation recommendations," Brussels, Belgium, 2020.

[35] Studio Roosegaarde, "Smart Highway." https://www.studioroosegaarde.net/project/smart-highway (accessed Dec. 21, 2021).

[36] BBC News, "Glow in the dark roads not glowing," 2014. https://www.bbc.com/news/technology-27187827 (accessed Dec. 21, 2021).

[37] Scottish Road Research Board, "Investigating the potential for reactive 'glowing' roads as an initiative on the Scottish road network," Glasgow, Scotland, 2014. Accessed: Dec. 18, 2021. [Online]. Available: https://www.transport.gov.scot/media/1566/glowing-roads-report-final.pdf

[38] SEStran / Scottish Road Research Board, "Star Path: Photo Luminescent Road Markings: Trial Study," Glasgow, Scotland, 2018. Accessed: Dec. 18, 2021. [Online]. Available: https://www.transport.gov.scot/media/42391/2018-19-srrb-star-path-final-report-4-jun-18.pdf

[39] Safety Path Support, "Road Safety Innovation Fund Grant for Safety Path ," 2020. https://safetypath.com/road-safety-innovation-fund-grant-for-safety-path/ (accessed Jan. 04, 2022).

[40] Z. Ovuka, "Safer Greener Better," 2021. https://roads.memnet.com.au/LocalisedFiles/DocumentManager/Spotlight%20on%20Safety%20-%20Zoran%20Ovuka.pdf (accessed Jan. 04, 2022).

[41] J. Nance and T. D. Sparks, "Comparison of coatings for SrAl2O4:Eu2+,Dy3+ powder in waterborne road striping paint under wet conditions," *Progress in Organic Coatings*, vol. 144, p. 105637, Jul. 2020, doi: 10.1016/j.porgcoat.2020.105637.

[42] C. Villa, R. Bremond, F. Eymond, and E. Saint-Jacques, "CHARACTERISATION OF LUMINESCENT ROAD MARKINGS," in *Proceedings of the Conference CIE 2021*, Dec. 2021, pp. 22–31. doi: 10.25039/x48.2021.OP02.

[43] J. Nance and T. D. Sparks, "From streetlights to phosphors: A review on the visibility of roadway markings," *Progress in Organic Coatings*, vol. 148, p. 105749, Nov. 2020, doi: 10.1016/j.porgcoat.2020.105749.

[44] J. L. Campbell *et al.*, *Human Factors Guidelines for Road Systems: Second Edition*. Washington, D.C.: Transportation Research Board, 2012. doi: 10.17226/22706.

[45] H. G. Hawkins, "Research on Traffic Sign Retroreflective Sheeting Performance: A Synthesis of Practice," St. Paul, Minnesota, USA, 2021.

[46] M. Sivak, M. Flannagan, and A. W. Gellatly, "Influence of truck driver eye position on effectiveness of retroreflective traffic signs," *Lighting Research and Technology*, vol. 25, no. 1, pp. 31–36, Jan. 1993, doi: 10.1177/096032719302500105.

[47] 3M, "3 trends that impact road sign performance ." https://www.3m.com/3M/en_US/road-safety-us/resources/road-transportation-safety-center-blog/full-story/?storyid=8be3482c-d78a-4a33-8ce3-dffdbd6ebd9a (accessed Mar. 04, 2022).

[48] UNECE, "The Vienna Convention on Road Signs and Signals," 1968.

[49] United Nations: Working Party on Road Traffic Safety, "Convention on Road Signs and Signals (1968): Group of Experts on Road Signs and Signals." United Nations, 2013. Accessed: Jan. 17, 2021. [Online]. Available: https://unece.org/DAM/trans/main/wp1/tor/ECE-TRANS-WP.1-2013-2-Rev1e_.pdf

[50] Group of Experts on Road Signs and Signals, "Draft final report of the Group of Experts on Road Signs and Signals," Geneva, Switzerland, 2019. Accessed: Jan. 17, 2021. [Online]. Available: https://unece.org/DAM/trans/doc/2019/wp1/ECE-TRANS-WP1-GE2-2018-5-Rev1e_01.pdf

[51] European Committee for Standardization, "EN 12899-1:2007: Fixed, vertical road traffic signs - Part 1: Fixed signs," Brussels, Belgium, 2007.

[52] European Organisation for Technical Assessment, "Microprismatic retro-reflective sheetings," Brussels, Belgium, 2015.

[53] European Union, "Commission Delegated Regulation (EU) 2021/1958." European Union, 2021. Accessed: Jan. 19, 2021. [Online]. Available: https://eur-lex.europa.eu/eli/reg_del/2021/1958/oj

[54] T. Ben-Bassat, "Are ergonomically designed road signs more easily learned?," *Applied Ergonomics*, vol. 78, pp. 137–147, Jul. 2019, doi: 10.1016/j.apergo.2019.02.009.

[55] T. Ben-Bassat and D. Shinar, "Ergonomic Guidelines for Traffic Sign Design Increase Sign Comprehension," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 48, no. 1, pp. 182–195, Mar. 2006, doi: 10.1518/001872006776412298.

[56] Austroads, "Implications of Traffic Sign Recognition (TSR) Systems for Road Operators," Sydney, Australia, 2018.

[57] E. Salahat, H. Saleh, A. Sluzek, M. Al-Qutayri, B. Mohammed, and M. Ismail, "Evolutionary QR-Based Traffic Sign Recognition System for Next-Generation Intelligent Vehicles," in *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, Sep. 2015, pp. 1–5. doi: 10.1109/VTCFall.2015.7390939.

[58] J. Snyder, D. Dunn, J. Howard, T. Potts, and K. Hansen, "'Invisible' 2D Bar Code to Enable Machine Readability of Road Signs – Material and Software Solutions," St. Paul, Minnesota, USA, 2018. Accessed: Jan. 17, 2021. [Online]. Available: https://multimedia.3m.com/mws/media/1584051O/2d-barcode-whitepaper.pdf

[59] J. García Oya, R. Martín Clemente, E. Hidalgo Fort, R. González Carvajal, and F. Muñoz Chavero, "Passive RFID-Based Inventory of Traffic Signs on Roads and Urban Environments," *Sensors*, vol. 18, no. 7, p. 2385, Jul. 2018, doi: 10.3390/s18072385.

[60] Y. Sato and K. Makanae, "Development and Evaluation of In-vehicle Signing System Utilizing RFID tags as Digital Traffic Signs," *International Journal of ITS Research*, vol. 4, no. 1, pp. 53–58, 2006.

[61] J. Pérez, F. Seco, V. Milanés, A. Jiménez, J. C. Díaz, and T. de Pedro, "An RFID-Based Intelligent Vehicle Speed Controller Using Active Traffic Signals," *Sensors*, vol. 10, no. 6, pp. 5872–5887, Jun. 2010, doi: 10.3390/s100605872.

[62] A. Paul, N. Bharadwaj, A. S. Bhat, S. Shroff, V. Seenanna, and T. Sitharam, "Design and prototype of an in-vehicle road sign delivery system using RFID," in *2012 12th International Conference on ITS Telecommunications*, Nov. 2012, pp. 220–225. doi: 10.1109/ITST.2012.6425170.

[63] F. Mariut, C. Fosalau, C. Zet, and D. Petrisor, "Experimental traffic sign detection using I2V communication," in *2012 35th International Conference on Telecommunications and Signal Processing (TSP)*, Jul. 2012, pp. 141–145. doi: 10.1109/TSP.2012.6256269.

[64] J. García Oya, R. Martín Clemente, E. Hidalgo Fort, R. González Carvajal, and F. Muñoz Chavero, "Passive RFID-Based Inventory of Traffic Signs on Roads and Urban Environments," *Sensors*, vol. 18, no. 7, p. 2385, Jul. 2018, doi: 10.3390/s18072385.

[65] M. Balog, E. Szilagyi, and M. Mindas, "Traffic Signs in Urban Logistics with the Use of RFID Technology," 2016, pp. 584–591. doi: 10.1007/978-3-319-33681-7_49.

[66] Ltd. Croatian Roads, "Application of RFID technology on road signs for the purpose of automatic update of road signs inventory." Zagreb, Croatia, 2022.

[67] B. Konopka, "Scientists create 'smart' road signs that use radar to warn drivers about hazards ahead," 2020. https://www.thefirstnews.com/article/scientists-create-smart-road-signs-that-use-radar-to-warn-drivers-about-hazards-ahead-18222 (accessed Jan. 21, 2022).

[68] J. Zeng, W. Fan, K. Jia, S. Tu, and L. Wu, "Novel Retroreflective Structural Color Films Based on Total Internal Reflection Interference," *Journal of Colloid and*

Interface Science, vol. 597, pp. 306–313, Sep. 2021, doi: 10.1016/j.jcis.2021.03.175.

[69] J. Rada *et al.*, "Multiple concentric rainbows induced by microscale concave interfaces for reflective displays," *Applied Materials Today*, vol. 24, p. 101146, Sep. 2021, doi: 10.1016/j.apmt.2021.101146.

[70] ITS Internationl, "Self-illuminating road signs star from HR Groep," 2016. https://www.itsinternational.com/products/self-illuminating-road-signs-star-hr-groep (accessed Dec. 19, 2021).

[71] C. K. Toh, J. Cano, C. Fernandez-Laguia, P. Manzoni, and C. T. Calafate, "Wireless digital traffic signs of the future," *IET Networks*, vol. 8, no. 1, pp. 74–78, Jan. 2019, doi: 10.1049/iet-net.2018.5127.

[72] W.-C. Ma *et al.*, "Exploiting Sparse Semantic HD Maps for Self-Driving Vehicle Localization," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Nov. 2019, pp. 5304–5311. doi: 10.1109/IROS40897.2019.8968122.

[73] G. Abdelkader, K. Elgazzar, and A. Khamis, "Connected Vehicles: Technology Review, State of the Art, Challenges and Opportunities," *Sensors*, vol. 21, no. 22, p. 7712, Nov. 2021, doi: 10.3390/s21227712.

[74] Autocrypt, "DSRC vs. C-V2X: A Detailed Comparison of the 2 Types of V2X Technologies," 2021. https://autocrypt.io/dsrc-vs-c-v2x-a-detailed-comparison-of-the-2-types-of-v2x-technologies/ (accessed Jan. 18, 2022).

[75] H. G. Seif and X. Hu, "Autonomous Driving in the iCity—HD Maps as a Key Challenge of the Automotive Industry," *Engineering*, vol. 2, no. 2, pp. 159–162, Jun. 2016, doi: 10.1016/J.ENG.2016.02.010.

[76] 5G Automotive Association, "C-V2X use cases methodology, examples and service level requirements," München, Germany, 2019.

[77] 5G Automotive Association, "C-V2X use cases volume II: Examples and service level requirements," München, Germany, 2020.

[78] V. Mannoni, V. Berg, S. Sesia, and E. Perraud, "A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X," in *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, Apr. 2019, pp. 1–5. doi: 10.1109/VTCSpring.2019.8746562.

[79] D. Demuynck, "Elektrobit and TomTom partnership to accelerate safe automated driving," 2020. https://www.tomtom.com/blog/automated-driving/new-version-autostream-for-safe-automated-driving/ (accessed Jan. 18, 2022).

[80] P. Zhang, M. Zhang, and J. Liu, "Real-Time HD Map Change Detection for Crowdsourcing Update Based on Mid-to-High-End Sensors," *Sensors*, vol. 21, no. 7, p. 2477, Apr. 2021, doi: 10.3390/s21072477.

[81] K. Kim, S. Cho, and W. Chung, "HD Map Update for Autonomous Driving With Crowdsourced Data," *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 1895–1901, Apr. 2021, doi: 10.1109/LRA.2021.3060406.

[82] D. Tchuente, D. Senninger, H. Pietsch, and D. Gasdzik, "Providing more regular road signs infrastructure updates for connected driving: A crowdsourced approach with clustering and confidence level," *Decision Support Systems*, vol. 141, p. 113443, Feb. 2021, doi: 10.1016/j.dss.2020.113443.

[83] C. Kaufmann, M. Frühwirth, D. Messerschmidt, M. Moser, A. Eichberger, and S. Arefnezhad, "Driving and tiredness: Results of the behaviour observation of a simulator study with special focus on automated driving," *Transactions on Transport Sciences*, vol. 11, no. 2, pp. 51–63, Sep. 2020, doi: 10.5507/tots.2020.011.

[84] S. Arefnezhad, A. Eichberger, M. Frühwirth, C. Kaufmann, M. Moser, and I. V. Koglbauer, "Driver Monitoring of Automated Vehicles by Classification of Driver Drowsiness Using a Deep Convolutional Neural Network Trained by Scalograms of ECG Signals," *Energies (Basel)*, vol. 15, no. 2, p. 480, Jan. 2022, doi: 10.3390/en15020480.

[85] World Road Association (PIARC), "Task Force B.2 Automated Vehicle: Challenges and opportunities for road operators and road authorities," Cedex, France.

[86] J. Guerrero-Ibáñez, S. Zeadally, and J. Contreras-Castillo, "Sensor Technologies for Intelligent Transportation Systems," *Sensors*, vol. 18, no. 4, p. 1212, Apr. 2018, doi: 10.3390/s18041212.

[87] H. P. Dai Nguyen and R. Zoltan, "The Current Security Challenges of Vehicle Communication in the Future Transportation System," in *2018 IEEE 16th International Symposium on Intelligent Systems and Informatics (SISY)*, Sep. 2018, pp. 000161–000166. doi: 10.1109/SISY.2018.8524773.

[88] A. Greenberg, "Hackers Remotely Kill a Jeep on the Highway—With Me in It," 2021. https://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway/ (accessed Jan. 19, 2022).

[89] M. Cebe, E. Erdin, K. Akkaya, H. Aksu, and S. Uluagac, "Block4Forensic: An Integrated Lightweight Blockchain Framework for Forensics Applications of Connected Vehicles," *IEEE Communications Magazine*, vol. 56, no. 10, pp. 50–57, Oct. 2018, doi: 10.1109/MCOM.2018.1800137.

[90] Rathee, Sharma, Iqbal, Aloqaily, Jaglan, and Kumar, "A Blockchain Framework for Securing Connected and Autonomous Vehicles," *Sensors*, vol. 19, no. 14, p. 3165, Jul. 2019, doi: 10.3390/s19143165.

[91] Thales Group, "V2X: What is Vehicle to Everything?," 2021. https://www.thalesgroup.com/en/markets/digital-identity-and-security/iot/industries/automotive/use-cases/v2x (accessed Jan. 21, 2022).

[92] Audi MediaCenter, "Audi networks with traffic lights in the USA," 2016. https://www.audi-mediacenter.com/en/press-releases/audi-networks-with-traffic-lights-in-the-usa-7147 (accessed Jan. 06, 2022).

[93] Audi MediaCenter, "Tech talk: Audi, Traffic Light Information and the future of what—and how—to drive." https://media.audiusa.com/en-us/releases/412 (accessed Jan. 08, 2022).

[94] E. Klochikhin, "Intelligent Parking: A Tale of Five Cities," 2018. https://medium.com/predict/intelligent-parking-a-tale-of-five-cities-31b14056261 (accessed Feb. 08, 2022).

[95] B. Mukhopadhyay and T. Samanta, "A Smart Parking-lot Occupancy Model in 5G V2V and V2I Wireless Communication," in *2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sep. 2021, pp. 1552–1557. doi: 10.1109/PIMRC50174.2021.9569337.

[96] W. Balzano and F. Vitale, "DiG-Park: A Smart Parking Availability Searching Method Using V2V/V2I and DGP-Class Problem," in *2017 31st International*

Conference on Advanced Information Networking and Applications Workshops (WAINA), Mar. 2017, pp. 698–703. doi: 10.1109/WAINA.2017.104.

[97] Drive Sweden, "Autonomous Driving Aware Traffic Control – Final Report," 2017. Accessed: Feb. 08, 2022. [Online]. Available: https://www.drivesweden.net/sites/default/files/content/ad_aware_traffic_control_-_final_report_v11_0.pdf

[98] H. Shimada, A. Yamaguchi, H. Takada, and K. Sato, "Implementation and Evaluation of Local Dynamic Map in Safety Driving Systems," *Journal of Transportation Technologies*, vol. 05, no. 02, pp. 102–112, 2015, doi: 10.4236/jtts.2015.52010.

[99] TomTom, "How do HD maps extend the vision of autonomous vehicles?" Amsterdam, The Netherlands. Accessed: Feb. 08, 2022. [Online]. Available: https://download.tomtom.com/open/banners/Elektrobit_TomTom_whitepaper.pdf

[100] Austroads, "Infrastructure changes to support automated vehicles on rural and metropolitan highways and freeways: Road Audit (Module 2)," Sydney, Australia, 2019.

[101] Financial Times, "Bosch and Continental acquire stake in digital maps service Here," 2018. https://www.ft.com/content/af188452-f127-11e7-b220-857e26d1aca4 (accessed Feb. 01, 2022).

[102] TomTom, "Maps." https://www.tomtom.com/products/map-technology/ (accessed Feb. 01, 2022).

[103] HERE, "Boosting driver awareness, comfort and safety with enhanced ADAS." 2021. Accessed: Feb. 01, 2022. [Online]. Available: https://go.engage.here.com/rs/142-UEL-347/images/HERE_eBook_Boosting_awareness_comfort_safety_through_ADAS.pdf

[104] TomTom, "Use Case: Intelligent Speed Assistance." https://www.tomtom.com/use-cases/intelligent-speed-assistance/ (accessed Feb. 01, 2022).

[105] European Union, "Commission Delegated Regulation (EU) 2021/1958." 2021.

[106] TomTom, "Use Case: Predictive Powertrain Control." https://www.tomtom.com/use-cases/predictive-powertrain-control/ (accessed Jan. 05, 2022).

[107] Mercedes-Benz, "Kraftstoffsparender fahren – mit Predictive Powertrain Control." https://www.mercedes-benz-trucks.com/de_AT/models/the-actros/efficiency/predictive-powertrain-control.html (accessed Feb. 02, 2022).

[108] B. Alrifaee, M. Reiter, J. P. Maschuw, F. Christen, L. Eckstein, and D. Abel, "Satellite- and Map-based Long Range Cooperative Adaptive Cruise Control System for Road Vehicles," *IFAC Proceedings Volumes*, vol. 46, no. 21, pp. 732–737, 2013, doi: 10.3182/20130904-4-JP-2042.00150.

[109] E. Talavera, A. Díaz-Álvarez, F. Jiménez, and J. Naranjo, "Impact on Congestion and Fuel Consumption of a Cooperative Adaptive Cruise Control System with Lane-Level Position Estimation," *Energies (Basel)*, vol. 11, no. 1, p. 194, Jan. 2018, doi: 10.3390/en11010194.

[110] R. Utriainen, M. Pollanen, and H. Liimatainen, “The Safety Potential of Lane Keeping Assistance and Possible Actions to Improve the Potential,” *IEEE Transactions on Intelligent Vehicles*, vol. 5, no. 4, pp. 556–564, Dec. 2020, doi: 10.1109/TIV.2020.2991962.

[111] M. Tsogas, A. Polychronopoulos, and A. Amditis, “Using digital maps to enhance lane keeping support systems,” in *2007 IEEE Intelligent Vehicles Symposium*, Jun. 2007, pp. 148–153. doi: 10.1109/IVS.2007.4290106.

[112] J. Wang, S. Schroedl, K. Mezger, R. Ortloff, A. Joos, and T. Passegger, “Lane Keeping Based on Location Technology,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 3, pp. 351–356, Sep. 2005, doi: 10.1109/TITS.2005.853701.

[113] Croatian Roads Ltd., “Road signs and road markings database in Croatia.”

[114] Goverment of the Netherlands, “Traffic signs in the Netherlands now available online,” 2020. https://www.government.nl/latest/news/2020/08/04/traffic-signs-in-the-netherlands-now-available-online (accessed Jan. 14, 2022).

TABLES AND FIGURES

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Social-cost benefit analysis of a common approach as regards road markings' visibility and width

Final report of the WP5

February, 2023

Directorate-General for Mobility and Transport
Study on road signs and road markings

SUMMARY

As part of the traffic control plan, road markings and road signs provide road users with information regarding the current and upcoming road situation.

The revised Road Infrastructure Safety Management Directive[1] has included new provisions on lane markings and road signs. Member States in particular has been requested to pay specific attention, in their existing and future procedures for road markings and road signs, to readability and detectability for human drivers and automated driver assistance systems.

The Commission has been tasked to set up a group of experts to assess the opportunity to establish common specifications including different elements aiming at ensuring the operational use of road markings and road signs in order to foster the effective readability and detectability of road markings and road signs for human drivers and automated driver assistance systems.

The expert Group on Road Infrastructure Safety – hereafter referred to as “EGRIS” was created in December 2019 and was tasked to assist it in relation to the implementation of the required provisions of the Directive. One of the tasks of EGRIS is, with the help of the sub-group Road Markings and Road Signs, to advise and support the Commission on how to improve the readability and detectability of road markings and road signs, both for human drivers and ADAS systems. The overall aim of this study is to provide the Commission with an up-to-date information to support the work of the MS’ experts for the implementation of Article 6(c) of the Directive.

From the overall discussions of the expert group, it was decided to focus on road markings.

In order to establish whether a common approach, in the form of common technical specifications or guidelines for road markings in terms of visibility and width generates road safety benefits, the EGRIS group decided to base its further assessment on two analyses: 1) a social cost-benefit; and 2) a break-even cost-benefit. In this part of the report a social cost-benefit analyses for each member state is presented.

A social or societal cost-benefit analysis of a new road safety measure is a financial calculation that weighs the costs of the investment of a new measure against the societal benefits that the new measure is expected to deliver (e.g. saving of road casualties). Such analysis indicates whether the societal benefits weigh up against the investment in the measure. For that purpose, a monetary value is assigned to the benefits that are expected to result from the measure. This report summarises the methodology, assumptions, limitations and findings of this social cost-benefit analysis.

The results of this analysis serve as a first indication of the expected costs and benefits regarding visibility and width levels for road markings on motorways and primary roads in Europe. The findings refer to some Member States for which data was made available.

These preliminary results indicate that introducing common specifications for road markings can result in road safety benefits. For some common specifications, the results indicate a positive direction related to this introduction however the value of the effect is highly disputable. However, it is expected that introducing common specifications for road markings and signs will be inevitable in the future when autonomous vehicles will become more common.

[1] DIRECTIVE (EU) 2019/1936 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2019- amending Directive 2008/96/EC on road infrastructure safety management

CONTENT

1. INTRODUCTION

Road markings and signs are a fundamental element of road infrastructure as their main task is to provide timely and necessary information to the driver related to the upcoming situation. Put differently, they warn and inform drivers about the conditions and construction characteristics of the road, guide road users through the traffic network and regulate traffic in a safe way. Recently, road markings and signs have also become important for different vehicle systems, such as Advanced Driver Assistance Systems (ADAS).

When looking at road markings and signs, their effectiveness, for both humans and ADAS systems, depends on a several characteristics such as geometric, performance, operational etc. Generally, their use has been to some extent unified with the United Nation treaty on Road Signs and Signals from 1968. However, inconsistency between EU Member States still exist. In general, literature recognizes different ergonomic principles but most of the studies emphasize between three and five main ones: standardisation, compatibility, familiarity, simplicity and meaningfulness (Ben-Bassat, 2019; Ben-Bassat & Shinar, 2006; Ng & Chan, 2007; Yuan et al., 2014). Although these features are the main ones for the human driver, some of them (such as standardisation) may also play a significant role for the detectability and readability of different vehicle technologies.

Except the aforementioned ergonomic principles, performance characteristics, such as daytime and night-time visibility, chromaticity or colour contrast, play an important role in detection and readability of road markings and signs by humans and vehicles. Namely, in low visibility weather conditions (night, rain, fog etc.), these characteristics enable road markings and signs to “stand out” from the surrounding and thus be visible and comprehendible.

Although both the private sector and the national authorities in each Member State are pushing towards improving the overall quality of road markings and road signs, at least in some cases further efforts are needed. Current standards regarding road markings and road signs are based on human needs and to some extent may not be sufficient for the automated driver assistance systems (ADAS). Thus, a broader approach focusing on the needs and requirements of both human drivers and advanced vehicle systems is needed.

1.1. Purpose & scope

The analysis of current practices (carried out in WP1) revealed that road markings and road signs in Member States are regulated through national regulations, guidelines, specifications or standards. However, their performance level, i.e., quality characteristics as well as dimension and design differ among member states. Additionally, the results of a comprehensive literature analysis indicated that current standards for visibility of road markings, in some countries, may not be adequate for both human drivers and ADAS in all conditions.

Based on these insights the consortium identified an initial list of areas for which improvements could be considered. Through further work with the EGRIS experts, a narrowed list of areas regarding road markings width and visibility performance has been identified for further analysis. In order to further evaluate the potential and validity of the detailed options to be envisaged for each area, the consortium has carried out a socioeconomic assessment to estimate the costs and benefits for Member States associated with establishing minimum levels for road marking width and visibility performance for new road markings on motorways and primary roads. This report describes the results of this socioeconomic assessment. Therefore, the purpose of this report is to develop a preliminary cost information and estimate the potential benefit to cost ratio of improving road marking width and visibility performance for new road markings on motorways and primary roads.

The results of this assessment support the Commission and the Member States' experts in considering whether it is effective, desirable and feasible to implement a common approach in this field, possibly through common technical specifications or guidelines for new road markings on motorways and primary roads in the future.

1.2. Methodological process

During the EGRIS plenary meeting of February 28, 2022 the consortium presented the cost-benefit analysis approach that would be used to calculate the agreed common minimal visibility and width levels for road markings. The subject of this approach were new road markings on motorways and primary roads in Europe. Given that the RISM directive does not address maintenance of existing infrastructure, the latter was not in scope of this exercise.

The purpose of this CBA was to evaluate the effectiveness of the common visibility and width levels for road markings in dry/wet and day/night-time circumstances for both human drivers and ADAS in reducing road traffic injuries of different severity as well as to provide information on the socio-economic return of the different common minimal visibility and width levels for road markings. For that purpose, a monetary value is assigned to the costs and benefits of common minimal value. The benefits (B) are then compared to the costs (C) in order to calculate the cost-effectiveness of the measure. This decision is based on the benefit-to-cost ratio (BVR) = B/C:

- BCR < 1: the measure is not cost-effective and creates insufficient benefits

- BCR = 1: the benefits are equal to the investment costs of the measure. The measure generates no profits or losses.

- BCR > 1: the benefits are higher than the investment costs of the measure. The measure is cost-effective and generates sufficient benefits to consider implementation.

1.2.1. Cost components

The cost components of the cost benefit analysis consist of the following parameters:

- The costs to implement road markings of certain visibility levels and width taking the service life (expectable life time in years) into account. These costs are expressed as unit prices of several materials (Paint, Coldspray Plastic, ColdPlastic, Thermoplastic) and implementation options (flatline vs. structured). These costs have been sourced from the industry (SWARCO, GmbH). The costs used in this analysis only include material costs. Other implementation costs such as costs of traffic management / road works to apply the markings etc. are not included. The implementation costs depend on the service lifetime of the material (a shorter lifetime implies higher implementation costs over the same period of time) and the type of material itself (some materials are more time consuming to apply). The non-material related implementation costs, however, are independent of the retroreflectivity or width. Hence, when comparing scenarios of different levels of retroreflectivity or width, the non-material related implementation cost is not a decisive factor.

- The length in km of edge lines and centre lines on motorways and primary roads in each Member State. These lengths are estimated by the Member States' experts and are retrieved from the survey data of WP1.

- The current situation regarding road marking width and visibility levels on motorways and primary roads of each Member State. These values are provided by the Member States' experts and are retrieved from the survey data of WP1.

1.2.2. Benefit components

From a road safety perspective, the benefits represent the value of all casualties or crashes prevented by implementing the common minimal visibility and width values. Consequently, the road safety benefits that result from the introduction of these common minimal values in a certain period n, depending on the level of severity s, are calculated as follows:

$$Benefits_n = \sum_s Target\ crashes_s * \ Effectiveness\ _s * \ Injury\ cost_s$$

The target crashes are the number of injuries of various severity levels that can possibly be affected by the common minimal visibility and width values for road markings. The target crashes to estimate the effect of improved road marking are set to single-vehicle crashes whereas for ADAS, the target crashes are set to lane-changing crashes as several scientific studies found a beneficial impact (Carlson et al., 2009, 2013a; Chang et al., 2019; Cicchino, 2018; Hickman et al., 2015; Park et al., 2012; Penmetsa et al., 2019; Spicer et al., 2018; Sternlund, 2017).

The effectiveness of the common minimal visibility and width levels is expressed by crash modification factors (CMFs). CMFs are the percentage reduction of the number of crashes or casualties originating of introducing the measure. The information on the crash modification factors is retrieved from several scientific studies retrieved from the CMF Clearinghouse which is a highly respected CMF library that also scores the reliability of each CMF-study.

Subsequently, the benefits are expressed in monetary values by multiplying the number of prevented injuries with the monetary value of the benefit, i.e. the cost per injury sourced from Safetycube deliverable (D3.2)(Wijnen et al., 2017).

1.2.3. Member State feedback

After the presentation, the Member States provided feedback on the presented CBA approach. The general feedback indicated that the Member State do not support the use of CMFs as most CMFs in literature are from the USA or Australia and are considered not to be transferable to European conditions. Subsequently, some of the presented CMFs in the Clearinghouse were considered too high and overestimate the role of markings. However, CMFs already take the influence of other factors into account since crashes that are caused by alcohol, or other confounding factors were excluded from the datasets that the studies from the Clearinghouse used to calculate the CMFs. Despite CMF Clearinghouse being a widely adopted and well-proofed method to estimate the effectiveness of road safety measures (also scoring the reliability of each CMF study), the Member States, due to aforementioned reasons did not support this approach. Therefore, after several discussions and meetings, it was decided in June 2022 to abandon the use of CMFs and the approach described in section 2 of this report was selected as a compromise to evaluate the effectiveness of common visibility and width levels of road markings in Europe.

2. SOCIAL COST-BENEFIT ANALYSIS APPROACH

The economic appraisal approach that is applied to develop a preliminary cost information and estimate the potential benefit to cost ratio of establishing common specifications for road marking width and visibility performance is a social cost-benefit analysis.

A social or societal cost-benefit analysis of a new road safety measure is a financial calculation that weighs the costs of the investment of a new measure against the societal benefits that the new measure is expected to deliver (e.g. saving of road casualties). It returns whether the societal benefits weigh up against the investment in the measure. For that purpose, a monetary value is assigned to the benefits that are expected to result from the measure.

In this study, the costs are expressed as the implementation costs in terms of the material costs necessary to apply road markings of certain visibility levels and width on motorways and primary roads in a certain Member State. These implementation costs take a service life (expectable life time in years) of 4 years into account.

The cost component is calculated as follows:

*Length of centre + edge line markings (km) on motorways (primary roads) * (unit price of certain marking width, material and visibility level including service life over a 4-year period).*

The benefits are expressed as the saved costs in terms fatal injuries, serious injuries and slight injuries in single vehicle crashes (without alcohol involvement) on motorways and primary roads in a certain Member State due to implementing road markings of certain visibility levels and width.

The benefit component is calculated as follows:

*Number of fatal/serious/slight injured in a single vehicle crash on motorways/primary roads (during day/night, wet/dry circumstances) saved as a result of the implementation of the measure * Unit costs of a fatal, serious and slight injured.*

Finally, the total value of these benefits (B) is then compared to the costs (C) of the measure by calculating the benefit-cost ratio (BCR). Based on the BCR measures can be ranked or prioritized. The BCR can have three different value ranges:

- BCR < 1: the measure is not cost-effective and creates insufficient benefits
- BCR = 1: the benefits are equal to the investment costs of the measure. The measure generates no profits or losses.
- BCR > 1: the benefits are higher than the investment costs of the measure. The measure is cost-effective and generates sufficient benefits to consider implementation.

2.1. Area of application

The social cost-benefit analysis is carried out on all target crashes on European motorways and primary roads on which improved road marking can have an effect. As the road safety situation and specifications of road markings differ per Member State, the analysis is carried out on a Member State level (i.e. for each Member State separately). In this study, improved road marking is defined as road markings of a higher visibility and/or width than the current situation in each Member State. Furthermore, the focus of the social cost-benefit analysis lies on **new** road markings on European motorways and primary roads. Previous studies have identified that improved road marking may have a positive influence on single-vehicle crashes and on the effectiveness of lane-departure systems which assist in reducing single-vehicle crashes (Carlson et al., 2009, 2013b; Cicchino, 2018; Hickman et al., 2015; Park et al., 2012; Penmetsa et al., 2019; Spicer et al., 2018; Sternlund, 2017). Therefore, single-vehicle crashes are identified as the target crashes (crashes influenced by improved road marking) in our study. However, it is commonly known that single-vehicle crashes are often the result of alcohol-impaired driving. To limit the influence of confounding factors single-vehicle crashes in which alcohol-impairment played a role are therefore omitted from this study.

To summarize, the target crashes in this study are all single-vehicle crashes (without alcohol-impairment) on motorways and primary roads. This target crash type was also agreed upon during the last EGRIS-meeting of July 10th, 2022 in the presence with the Commission and the Member States' experts.

2.2. Road safety measures

As agreed upon during the EGRIS-meeting of December 15th, 2021 the social cost-benefit analysis is calculated for the following road marking widths and visibility levels.

2.2.1. Road marking visibility

The following areas will be further analysed and undergo a social cost and benefit analysis in order to decide on the most appropriate option(s) of each of the following areas:

- **Area 2 - common minimal levels for daytime visibility of new road markings**
    - Run a social cost and benefit analysis for 100, 130 and 160 $mcd*m^{-2}*lx^{-1}$ for motorways and primary roads
- **Area 3 – common minimal levels for night-time visibility of road markings for motorways and primary roads in dry conditions**
    - For motorways: run a social cost-benefit analysis on the following options: (a) 300 $mcd*m^{-2}*lx^{-1}$, (b) 200 $mcd*m^{-2}*lx^{-1}$, (c) 150 $mcd*m^{-2}*lx^{-1}$
    - For primary roads: run a social cost-benefit analysis on the following options: (a) 200 $mcd*m^{-2}*lx^{-1}$, (b) 150 $mcd*m^{-2}*lx^{-1}$
- **Area 4 - common minimal levels for night-time visibility of new road markings in wet conditions**
    - Run a social cost-benefit analysis for 35 and 50 $mcd*m^{-2}*lx^{-1}$ for motorways and primary roads

2.2.2. Road marking width

The following area will be further analysed and undergo a social cost and benefit analysis in order to decide on the most appropriate option(s):

- **Area 5 - common minimal width of road markings:**
    - For motorways: run a social cost-benefit analysis on the following options: (a) 15 cm/20 cm (centre lines/edge lines), (b) 15 cm/15 cm (centre lines/edge lines).
    - For primary roads, run a social cost-benefit analysis for 12 cm/12 cm (centre lines /edge lines)

2.3. Cost components

The cost components of the social cost benefit analysis consist of the following parameters:

- The costs to implement road markings of certain visibility levels and width taking the service life (expectable life time in years) into account. These costs are expressed as unit prices of several materials (Paint, Coldspray Plastic, ColdPlastic, Thermoplastic) and implementation options (flatline vs. structured). These costs have been sourced from the industry (SWARCO, GmbH). See annex 1.1 for an overview.

- The length in km of edge lines and centre lines on motorways and primary roads in each Member State. These lengths are estimated by the Member States' experts and are retrieved from the survey data of WP1. See annex 1.2 for an overview.

- The current situation regarding road marking width and visibility levels on motorways and primary roads of each Member State. These values are provided by the Member States' experts and are retrieved from the survey data of WP1. See annex 1.3 for an overview.

2.4. Benefit components

In this social cost-benefit analysis the benefits are expressed as the saved costs in terms fatal injuries, serious injuries and slight injuries in single vehicle crashes on motorways and primary roads in a certain Member State due to implementing road markings of certain visibility levels and width.

The benefit components of the social cost benefit analysis consist of the following parameters:

- Crash data (period 2017-2020) single vehicle crashes (without influence of alcohol impairment) from CARE database for each Member State (period 2017-2020). Four-years of data is used to control for random variation in the data. The data includes night-time single vehicle crashes (wet + dry) and day-time single-vehicle crashes (dry) on motorways and primary roads.
- The unit costs of a fatal, serious and slight injured person in each Member State. These costs have been sourced from Safetycube deliverable (D3.2)(Wijnen et al., 2017). The costs used in D3.2 originate from 2015. These costs/prices are converted to 2022 prices based on the current inflation level (June 2022) obtained from Eurostat (2022) and Inflation.eu (2022). For this purpose, the average harmonized index of consumer prices (HICP) is used as Eurostat uses this index to compare inflation in countries belonging to the European Union. The HICP represents a 'basket' of goods and services representative of the Eurozone. See annex 1.4 for an overview.

2.5. Assumptions in CBA

The key assumptions underpinning the social cost benefit analysis include:

- The costs and benefits are only calculated for new road markings on European motorways and primary roads.

- The social cost-benefit analysis is conducted for a period of four years because the average service life of the road markings is set equal to four years. The reason for this is that four years is the expectable life time of the most expensive material for which cost values are available (i.e. thermoplastic flatline road marking).

- The unit costs provided by the industry make a distinction between different materials that can be used to meet the common minimal visibility and width levels of road markings. In the social cost-benefit analysis we take the use of different materials to reach a certain visibility or width level into account as the material type influences the cost component. But the main focus lies on the visibility and width performance of road markings. Therefore, the purpose of this analysis is not to advise Member States on which material they should use. This decision is left to the Member States. This analysis simply provides an overview of the different possibilities that can be used to reach a certain visibility or width level.

- The costs and benefits are only calculated for Member States that do not yet meet the common minimal visibility levels of road markings during night-time (dry + wet), day-time (dry) and/or the common minimal width levels. In other words, Member States that currently apply higher width and visibility criteria or meet these criteria already are excluded from the analysis.

- In case a Member State currently applies a higher road marking width (than the common minimal defined road marking width) with a lower visibility level (than the common minimal defined visibility levels), the currently applied road marking width is kept in the social cost benefit analysis and combined with the common minimal defined visibility levels which the Member State currently does not meet.

- In case a Member State currently applies higher road marking visibility levels or already meets the common minimal defined road marking visibility levels but has a road marking width that is lower than the common minimal defined width levels, the currently applied road marking visibility level is kept in the social cost benefit analysis and combined with the common minimal defined width levels which the Member State currently does not meet.

- Some Member States also provided more than one visibility or width level to describe the current situation on their motorway and primary road network. In that case the consortium had to make the following assumptions:

  - In case a Member State mentions two values we set the current situation equal to the lowest value provided;

  - In case a Member State mentions three values we set the current situation equal to the middle value provided.

    Consequently, we use the upper bound of the costs in this analysis for the motorway or primary road network knowing that a part of the network already meets higher road marking widths the costs will then be higher than in reality but the benefits must then also be higher in order to create a beneficial effect for road safety. So, in the end, his approach is stricter for the payback effects of the measure.

- As mentioned above the average harmonized index of consumer prices (HICP) with the inflation level of June 2022 is used to convert the unit costs of a fatal, serious and slight injured person from 2015 to 2022 prices. If a Member State specific value of the HCIP is available this inflation value is used to calculate the actual prices. However, for a few Member States there is no specific inflation value available. For these Member States, the European average HCIP value of June 2022 is used to calculate the actual prices.

2.6. Limitations

The limitations of this study include:

- The costs and benefits are only calculated for Member States for which data is available:

  - For some Member States there is only partial information available about certain parameters (for example the length of edge lines and centre lines). In that case, the social cost-benefit data is calculated with this partial data (for example only for motorways or primary roads).

  - A Member State is excluded from the social cost benefit analysis in case there is no crash data, no information about the current road marking visibility and/or width or the length of edge and centre lines on motorways and primary roads.

- The costs to implement road markings of certain visibility levels and width taking the service life (expectable life time in years) into account originate from only 1 supplier. Therefore, these costs should be regarded as average costs and the results of the analysis give a first indication of the expected costs and benefits.

- The costs should also be regarded as average costs since the costs of implementing road markings of certain visibility levels and width may differ depending on the economic situation per Member State. This means that some Member State will pay lower market prices whereas others will pay higher market prices to implement the same visibility and width performance levels. So, for some Member States the costs used in this analysis are an over-/underestimation of the actual prices.

- The supplier did not provide unit costs and service life information for Qd 100 and 130 mcd*m^{-2}*lx^{-1}, RW 35 mcd*m^{-2}*lx^{-1} and R_L 150 mcd*m^{-2}*lx^{-1}. These visibility performance levels are therefore excluded from the analysis.

- The material costs used in the calculations originate from February 2022, current prices may be influenced by changing market conditions.

- The costs used in this analysis only include material costs. Other implementation costs such as costs of traffic management / road works to apply the markings etc. are not included. The implementation costs depend on the service lifetime of the material (a shorter lifetime implies higher implementation costs over the same period of time) and the type of material itself (some materials are more time consuming to apply). The non-material related implementation costs, however, are independent of the retroreflectivity or width. In other words, the personnel costs, time necessary to implement markings etc. are independent of the retroreflectivity level or width. Hence, when comparing scenarios of different levels of retroreflectivity or width, the non-material related implementation cost is not a decisive factor.

- As mentioned above, the average service life is set equal to 4 years (expectable life time of the most expensive material for which we have cost values (i.e. thermoplastic flatline road markings). However, markings can have a lower or longer life expectancy depending on a number of factors. It is commonly known that road markings can be damaged by winter maintenance works done by snow-ploughs, traffic density and the number of heavy vehicles, surface conditions, other normal weather influences like UV light, sand etc. These aspects are not considered in the analysis. Therefore, the results of the analysis serve as a first indication of the expected costs and benefits.

- For almost every Member State, the crash data retrieved from the CARE database suffers from underreporting due to missing information about for instance the type of road (motorway, primary road), weather/light conditions. These aspects are unknown for a portion of the single-vehicle crashes and accompanying injuries in the CARE database. Target crashes for which these aspects are unknown are left out of the analysis since it is impossible to find out the crash and injury characteristics. Therefore, it is expected the actual number of fatalities, slightly injured and severely injured is higher than the numbers used to perform the cost-benefit analysis.

- The effect of incremental higher visibility and width levels cannot be considered. This is only possible with Crash Modification Factors (CMFs). For this study, it means that the incremental change in visibility and width levels can only be considered in the cost side but not in the benefit side without using CMFs. To illustrate, in order to include this incremental change in the benefit side we should know or find a value indicating how many crashes are caused in Europe by bad marking visibility or a too narrow marking width (which is not available). For example, we should know how many crashes can be avoided if we go from a visibility of 100 to 130 to 150 $mcd*m^{-2}*lx^{-1}$ and this incremental change can only be measured by means of CMFs if they are available. For the same reason, the analysis cannot differentiate between the costs and benefits of improved road markings for human drivers or ADAS. This is only possible with the use of CMFs.

- The effects/benefits of improved road markings will be overestimated since we cannot be 100% confident that better markings will have the same effect on all these crashes and injuries. In the current analysis, a 100% effectiveness on target crashes is assumed, i.e., the improved marking reduces the target crashes to zero. CMFs could assist in lowering the overestimation, but there are no reliable CMFs available for the Europe. Furthermore, it is widely acknowledged that crashes are the results of interaction between multiple factors (road users, environment/road, vehicle). In this report, the focus only lies on determining the role that the visibility and/or width of road markings plays in crash occurrence/avoidance. It is extremely complicated to succeed in determining whether the visibility of the road markings played a role in the occurrence of an accident especially since this type of information is not available in the crash data base. Because of all these reasons, it is currently not possible to solve this overestimation and the assumed effectiveness on the target crashes is very likely not equal to 100% but to a lower percentage. This limitation has been communicated by the consultant but accepted by the member states in the EGRIS meeting of 10 June 2022.

3. MEMBER STATE RESULTS

This chapter presents the results of the social cost-benefit analysis per Member State. Each section starts with an overview of the current situation in the Member State, followed by the road marking measures that will be calculated, the input values that are used in the analysis and the results of the social cost-benefits analysis for the different road marking visibility and width criteria.

3.1. Austria

3.1.1. Current situation

3.1.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	5145	9000	14145
Primary road	Not available. Austria has no definition of primary roads		
Source: WP1 survey			

3.1.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20/30	15
Primary road	Not available. Austria has no definition of primary roads	
Note: 30 cm edge line at exits and entries; 2 – Expressways (2+2 and 2+1 lane roads); 3 – On the suburban and main urban and suburban motorways the module is: 25-15-25, on suburban secondary and urban traffic and neighbourhood the module is: 15-12-15, while on local roads (urban and extra-urban) the module is: 12-10-12.		
Source: WP1 survey		

3.1.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	Not available. Austria has no definition of primary roads.
Night-time: wet (RW)	35	
Day-time: dry (Qd)	100/130	
Source: WP1 survey		

3.1.2. Road marking measures to be calculated

Austrian ***motorways*** already meet the visibility criteria for R_L (200), RW (35) and Qd (100/130) mcd*m^{-2}*lx^{-1} but do not meet the common defined visibility criteria of R_L 300, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. However, for Qd it is unclear how many motorways meet 100 or 130 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 100 for the entire motorway network.

Furthermore, for the marking widths it is unclear how many edge lines meet a width of 20 or 30 cm. Therefore, it is assumed that the *edge line* width for the entire motorway network is currently equal to the lowest value provided namely 20 cm. As a result, the marking widths on the motorway network of 15 cm for centre lines and 20 cm for edge lines already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

The measures are only calculated for motorways since Austria has no definition for ***primary roads***.

Therefore, the social cost-benefit analysis is calculated for motorways only and for the following measures:

- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

3.1.3. Input values for social cost-benefit analysis

3.1.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	3.014.655,00	3.203.975,33
Serious injury	381.285,00	405.229,70
Slight injury	26.880,00	28.568,06
The average harmonised inflation of Austria in 2022: 6.28% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.1.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	3	0
	Seriously injured	20	3
	Slightly injured	66	12
Night-time: wet	Fatally injured	0	0
	Seriously injured	5	1
	Slightly injured	55	6
Day-time: dry	Fatally injured	2	0
	Seriously injured	31	7
	Slightly injured	123	26

3.1.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.1.4. Social cost-benefit analysis results

- **Motorway: R_L 300 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 13.737.600,00	€ 7.754.400,00	€ 9.315.000,00	€ 12.231.000,00	€ 10.800.000,00
20 cm edge line	€ 10.471.104,00	€ 5.910.576,00	€ 7.100.100,00	€ 9.322.740,00	€ 8.232.000,00
Total	€ 24.208.704,00	€ 13.664.976,00	€ 16.415.100,00	€ 21.553.740,00	€ 19.032.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 9.611.925,99	€ 8.104.594,00	€ 1.885.491,96		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,40	0,70	0,59	0,45	0,51
Severely injured	0,33	0,59	0,49	0,38	0,43
Slightly injured	0,08	0,14	0,11	0,09	0,10
Total	0,81	1,43	1,19	0,91	1,03

Average	1,08

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure) and thermoplastic (structure). Thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (1,08) indicates that the benefits are higher than the investment costs of the measure.

- **Motorway: RW 50 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 13.737.600,00	€ 7.754.400,00	€ 9.315.000,00	€ 12.231.000,00	€ 10.800.000,00
20 cm edge line	€ 10.471.104,00	€ 5.910.576,00	€ 7.100.100,00	€ 9.322.740,00	€ 8.232.000,00
Total	€ 24.208.704,00	€ 13.664.976,00	€ 16.415.100,00	€ 21.553.740,00	€ 19.032.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 0,00	€ 2.026.148,50	€ 1.571.243,30		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0	0	0	0	0
Severely injured	0,08	0,15	0,12	0,09	0,11
Slightly injured	0,06	0,11	0,10	0,07	0,08
Total	0,15	0,26	0,22	0,17	0,19
Average			0,20		

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years.

- **Motorway: Qd 130 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**
- The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.
- **Motorway: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 13.737.600,00	€ 7.754.400,00	€ 9.315.000,00	€ 12.231.000,00	€ 10.800.000,00
20 cm edge line	€ 10.471.104,00	€ 5.910.576,00	€ 7.100.100,00	€ 9.322.740,00	€ 8.232.000,00
Total	€ 24.208.704,00	€ 13.664.976,00	€ 16.415.100,00	€ 21.553.740,00	€ 19.032.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 6.407.950,66	€ 12.562.120,70	€ 3.513.871,38		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**

	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,26	0,47	0,39	0,30	0,34
Severely injured	0,52	0,92	0,77	0,58	0,66
Slightly injured	0,15	0,26	0,21	0,16	0,18
Total	0,93	1,65	1,37	1,04	1,18
Average			1,23		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure) and thermoplastic (flatline). Paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (1,23) indicates that the benefits are higher than the investment costs of the measure. This is the case for all materials except for paint (flatline).

3.2. Belgium

3.2.1. Current situation

3.2.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	Only input received for Wallonia		
Primary road	Only input received for Wallonia		
Source: WP1 survey			

3.2.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	20
Primary road	20	15
Source: WP1 survey		

3.2.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	25	Not requested
Day-time: dry (Qd)	160/130	160/130
Source: WP1 survey		

3.2.2. Road marking measures to be calculated

Belgian ***motorways*** already meet the visibility criteria for RL (150) and Qd (160/130) but do not meet the common visibility criteria of RL 200/300 and RW 35/50. However, for Qd it is unclear how many motorways meet 160 or 130. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 for the entire motorway network. Furthermore, the marking widths on the motorway network of 20 cm for centre lines and 30 cm for edge line are currently higher than the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines

Belgian ***primary roads*** already meet the visibility criteria for R_L (150) and Qd (160/130) but do not meet the common visibility criteria of RL 200 and RW 35/50. However, for Qd it is unclear how many primary roads meet 160 or 130. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 for the entire primary road network. Furthermore, the marking widths on the primary road network of 15 cm for centre lines and 20 cm for edge lines are currently higher than the criteria set in the study namely 12 cm for edge and centre lines.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

3.2.3. Input values for social cost-benefit analysis

3.2.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.021.091,00	2.209.456,68
Serious injury	307.364,00	336.010,32
Slight injury	19.766,00	21.608,19
The average harmonised inflation of Belgium in 2022: 9.32% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.2.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	14	No crash and injury data available
	Seriously injured	78	
	Slightly injured	833	
Night-time: wet	Fatally injured	6	
	Seriously injured	26	
	Slightly injured	358	
Day-time: dry	Fatally injured	6	
	Seriously injured	101	
	Slightly injured	1316	

3.2.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00
30 cm	€ 1.418,40	€ 973,50	€ 1.710,00

3.2.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads. Furthermore, for primary roads there is no crash and injury data available for the target crashes in the CARE database.

3.3. Bulgaria

3.3.1. Current situation

3.3.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	3200	1600	4800
Primary road	6000	3000	9000
Source: WP1 survey			

3.3.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	15
Primary road	15	10
Source: WP1 survey		

3.3.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.3.2. Road marking measures to be calculated

Bulgarian ***motorways*** already meet the highest visibility criteria set for Qd, RL and RW in this study. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 25 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, **no social cost-benefit analysis** for Bulgarian motorways is calculated.

Bulgarian ***primary roads*** already meet the highest visibility criteria set for Qd, RL and RW in this study. Furthermore, the edge line width (15 cm) is higher than the criteria set in the study namely 12 cm. However, the centre line width (10 cm) is lower than the criteria set in the study namely 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 300 $mcd*m-2*lx^{-1}$ with 12 cm for centre lines and 15 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 15 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 15 cm for edge lines

3.3.3. Input values for social cost-benefit analysis

3.3.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.355.315,00	1.447.205,36
Serious injury	220.390,00	235.332,44
Slight injury	57.267,00	61.149,70
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Bulgaria Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.3.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	12	33
	Seriously injured	26	66
	Slightly injured	88	224
Night-time: wet	Fatally injured	2	2
	Seriously injured	4	9
	Slightly injured	20	47
Day-time: dry	Fatally injured	37	48
	Seriously injured	105	123
	Slightly injured	278	468

3.3.3.3. Implementation costs for a service life of 4 years

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00

3.3.4. Social cost-benefit analysis results

- **Primary roads: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre lines	€ 3.663.360	€ 2.067.840	€ 2.484.000	€ 3.261.600	€ 2.880.000
15 cm edge lines	€ 9.158.400	€ 5.169.600	€ 6.210.000	€ 8.154.000	€ 7.200.000
Total	€ 12.821.760	€ 7.237.440	€ 8.694.000	€ 11.415.600	€ 10.080.000
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 47.757.776,88	€ 15.531.941,04	€ 13.697.532,80		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	3,72	6,60	5,49	4,18	4,74
Severely injured	1,21	2,15	1,79	1,36	1,54
Slightly injured	1,07	1,89	1,58	1,20	1,36
Total	6,00	10,64	8,86	6,74	7,64
Average	7,98				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (7,98) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: RW 50 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre lines	€ 3.663.360,00	€ 2.067.840,00	€ 2.484.000,00	€ 3.261.600,00	€ 2.880.000,00
15 cm edge lines	€ 9.158.400,00	€ 5.169.600,00	€ 6.210.000,00	€ 8.154.000,00	€ 7.200.000,00
Total	€ 12.821.760,00	€ 7.237.440,00	€ 8.694.000,00	€ 11.415.600,00	€ 10.080.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.894.410,72	€ 2.117.991,96	€ 2.874.035,90		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,23	0,40	0,33	0,25	0,29
Severely injured	0,17	0,29	0,24	0,19	0,21
Slightly injured	0,22	0,40	0,33	0,25	0,29
Total	0,62	1,09	0,91	0,69	0,78
Average	0,82				

According to the comparison of the BCR the only cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline). Coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective.

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre lines	€ 3.663.360,00	€ 2.067.840,00	€ 2.484.000,00	€ 3.261.600,00	€ 2.880.000,00
15 cm edge lines	€ 9.158.400,00	€ 5.169.600,00	€ 6.210.000,00	€ 8.154.000,00	€ 7.200.000,00
Total	€ 12.821.760,00	€ 7.237.440,00	€ 8.694.000,00	€ 11.415.600,00	€ 10.080.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 69.465.857,28	€ 28.945.890,12	€ 28.618.059,60		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	5,42	9,60	7,99	6,09	6,89
Severely injured	2,26	4,00	3,33	2,54	2,87
Slightly injured	2,23	3,95	3,29	2,51	2,84
Total	9,91	17,55	14,61	11,13	12,60
Average	13,16				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (13,16) indicates that the benefits are higher than the investment costs of the measure.

3.4. Croatia

3.4.1. Current situation

3.4.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	17238	8638	25876
Primary road	10763	7175	17938
Source: WP1 survey			

3.4.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	20
Primary road	12/15	12/15
Source: WP1 survey		

3.4.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	200
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	160	130
Source: WP1 survey		

3.4.2. Road marking measures to be calculated

The road markings on ***motorways*** in Croatia meet the visibility and width levels recommended by the study or have higher visibility and width levels in place. As a result, there is no need to calculate a social cost-benefit analysis.

Croatian ***primary roads*** meet the visibility criteria for R_L (200), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$, but do not meet the common visibility criterion of Qd 160 $mcd*m^{-2}*lx^{-1}$. The marking width also meets the recommendation of 12 cm for edge and centre lines. On some parts of the network the width is equal to 15 cm. However, it is unclear which parts of the network have a marking width of 12 or 15 cm. Therefore, it is assumed that the edge and centre line width for the entire network is equal to 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measure:

- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines

3.4.3. Input values for social cost-benefit analysis

3.4.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.230.967,00	2.382.226,56
Serious injury	290.042,00	309.706,85
Slight injury	22.259,00	23.768,16
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Croatia Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.4.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	10	0
	Seriously injured	21	0
	Slightly injured	85	0
Night-time: wet	Fatally injured	2	0
	Seriously injured	11	0
	Slightly injured	29	1
Day-time: dry	Fatally injured	6	0
	Seriously injured	68	0
	Slightly injured	217	15

3.4.3.3. Unit costs of road marking materials including service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00

3.4.4. Social cost-benefit analysis results

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre + edge lines	€ 21.904.450,56	€ 12.364.304,64	€ 14.852.664,00	€ 19.502.193,60	€ 17.220.480,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 0,00	€ 0,00	€ 356.522,40		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,00	0,00	0,00	0,00	0,00
Severely injured	0,00	0,00	0,00	0,00	0,00
Slightly injured	0,02	0,03	0,02	0,02	0,02
Total	0,02	0,03	0,02	0,02	0,02
Average	0,02				

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective. This result is probably caused by the fact that from 2017-2020 the single-vehicle crashes on primary roads did not result in fatally injured or seriously injured. Therefore, the actual cost-effectiveness of the measure is expected to be higher than presented.

3.5. Cyprus

3.5.1. Current situation

3.5.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.5.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	20
Primary road	10/15	10/15
Source: WP1 survey		

3.5.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.5.2. Road marking measures to be calculated

Motorways in Cyprus meet the visibility criteria for R_L (200), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 20 cm for centre lines and edge lines already meet or are higher than the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 20 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 20 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 20 cm for centre lines and 20 cm for edge lines

Primary roads in Cyprus meet the visibility criteria for R_L (200), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge and centre lines meet a width of 10 or 15 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. As a result, the current edge and centre line width (10 cm) is lower than criteria set in the study namely 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- RW 50 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines

3.5.3. Input values for social cost-benefit analysis

3.5.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.027.088,00	1.096.724,57
Serious injury	135.535,00	144.724,27
Slight injury	9.921,00	10.593,64
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Cyprus Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.5.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	
	Seriously injured		
	Slightly injured		
Night-time: wet	Fatally injured		
	Seriously injured		
	Slightly injured		
Day-time: dry	Fatally injured		
	Seriously injured		
	Slightly injured		

3.5.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / RL 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

3.5.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads. Furthermore, there is no crash and injury data available for the target crashes in the CARE database.

3.6. Estonia

3.6.1. Current situation

3.6.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No roads classified as motorways		
Primary road	No data delivered		
Source: WP1 survey			

3.6.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20/30	15
Primary road	10/15/20/30	10/15
Source: WP1 survey		

3.6.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.6.2. Road marking measures to be calculated

Estonia has no roads classified as ***motorways*** so there is no need to calculate a social cost-benefit analysis for road marking width and visibility levels on motorways.

Primary roads in Estonia meet the visibility criteria for R_L (150), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria for R_L 200, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge lines meet a width of 10, 15, 20 or 30 cm and how many centre lines meet a width of 10 or 15 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. As a result, the current edge and centre line width (10 cm) is lower than criteria set in the study namely 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines

3.6.3. Input values for social cost-benefit analysis

3.6.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.819.426,00	3.010.583,08
Serious injury	959.011,00	1.024.031,95
Slight injury	36.802,00	39.297,18

The average harmonised inflation of Europe in 2022: 6.78%*

*Note: European average used since there is no specific HICP value available for Estonia

Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)

3.6.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	2
	Seriously injured		1
	Slightly injured		34
Night-time: wet	Fatally injured		2
	Seriously injured		2
	Slightly injured		18
Day-time: dry	Fatally injured		3
	Seriously injured		1
	Slightly injured		64

3.6.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 $mcd*m^{-2}*lx^{-1}$					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00

R_L 200 / Qd 160 $mcd*m^{-2}*lx^{-1}$			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00

3.6.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on primary roads.

3.7. Finland

3.7.1. Current situation

3.7.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	3700	1900	5600
Primary road	26000	13000	39000
Source: WP1 survey			

3.7.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	10
Primary road	10	10
Note : Centre line can be 30 cm or 40 cm (or 60 cm) on motorway weaving sections. Edge line can be 30 cm or 40 cm on primary roads or motorway weaving sections and even up to 60 cm on motorway weaving sections.		
Source: WP1 survey		

3.7.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	Not requested	Not requested
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.7.2. Road marking measures to be calculated

Finnish ***motorways*** already meet the visibility criteria for R_L (150) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200/300, RW 35/50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Currently, Finland applies a width of 10 cm for centre lines. This width is lower than the common width criterion of 15 cm. The currently applied edge line width of 20 cm meets the common width criterion of 20 cm set in this study.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

Finnish ***primary roads*** already meet the visibility criteria for R_L (150) and Qd (130) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criteria of R_L 200, RW 35/50 and

Qd 160 mcd*m^{-2}*lx^{-1}. Currently, Finland applies a width of 10 cm for edge and centre lines. This width is lower than the commonly defined width criterion of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 12 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 12 cm for edge lines

3.7.3. Input values for social cost-benefit analysis

3.7.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.340.452,00	2.468.006,63
Serious injury	671.383,00	707.973,37
Slight injury	29.111,00	30.697,55
The average harmonised inflation of Finland in 2022: 5.45%		
Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.7.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	1	14
	Seriously injured	5	29
	Slightly injured	55	251
Night-time: wet	Fatally injured	1	2
	Seriously injured	4	5
	Slightly injured	42	86
Day-time: dry	Fatally injured	2	17
	Seriously injured	10	32
	Slightly injured	95	316

3.7.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.7.4. Social cost-benefit analysis results

- **Motorways: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 1.347.480,00	€ 924.825,00	€ 1.624.500,00
20 cm edge line	€ 3.498.720,00	€ 2.401.300,00	€ 4.218.000,00
Total	€ 4.846.200,00	€ 3.326.125,00	€ 5.842.500,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.468.006,63	€ 3.539.866,85	€ 1.688.365,25
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	0,51	0,74	0,42
Severely injured	0,73	1,06	0,61
Slightly injured	0,35	0,51	0,29
Total	1,59	2,31	1,32
Average	1,74		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (1,74) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 2.900.160,00	€ 1.637.040,00	€ 1.966.500,00	€ 2.582.100,00	€ 2.280.000,00
20 cm edge line	€ 7.530.240,00	€ 4.250.560,00	€ 5.106.000,00	€ 6.704.400,00	€ 5.920.000,00
Total	€ 10.430.400,00	€ 5.887.600,00	€ 7.072.500,00	€ 9.286.500,00	€ 8.200.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.468.006,63	€ 3.539.866,85	€ 1.688.365,25		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,24	0,42	0,35	0,27	0,30
Severely injured	0,34	0,60	0,50	0,38	0,43
Slightly injured	0,16	0,29	0,24	0,18	0,21
Total	0,74	1,31	1,09	0,83	0,94
Average	0,98				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldPlastic (structure). Thermoplastic (structure), thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (0,98) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: RW 35 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 $mcd*m^{-2}*lx^{-1}$. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 $mcd*m^{-2}*lx^{-1}$. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 $mcd*m^{-2}*lx^{-1}$ differs.

- **Motorways: RW 50(mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 2.900.160,00	€ 1.637.040,00	€ 1.966.500,00	€ 2.582.100,00	€ 2.280.000,00
20 cm edge line	€ 7.530.240,00	€ 4.250.560,00	€ 5.106.000,00	€ 6.704.400,00	€ 5.920.000,00
Total	€ 10.430.400,00	€ 5.887.600,00	€ 7.072.500,00	€ 9.286.500,00	€ 8.200.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.468.006,63	€ 2.831.893,48	€ 1.289.297,10		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,24	0,42	0,35	0,27	0,30
Severely injured	0,27	0,48	0,40	0,30	0,35
Slightly injured	0,12	0,22	0,18	0,14	0,16
Total	0,63	1,12	0,93	0,71	0,80
Average			0,84		

According to the comparison of the BCR the only cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline). Coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (0,84) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 2.900.160,00	€ 1.637.040,00	€ 1.966.500,00	€ 2.582.100,00	€ 2.280.000,00
20 cm edge line	€ 7.530.240,00	€ 4.250.560,00	€ 5.106.000,00	€ 6.704.400,00	€ 5.920.000,00
Total	€ 10.430.400,00	€ 5.887.600,00	€ 7.072.500,00	€ 9.286.500,00	€ 8.200.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 4.936.013,26	€ 7.079.733,70	€ 2.916.267,25		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,47	0,84	0,70	0,53	0,60
Severely injured	0,68	1,20	1,00	0,76	0,86
Slightly injured	0,28	0,50	0,41	0,31	0,36
Total	1,43	2,54	2,11	1,61	1,82
Average			1,90		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (1,90) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: RL 200 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm centre + edge line	€ 22.127.040,00	€ 15.186.600,00	€ 26.676.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 34.552.092,82	€ 20.531.227,73	€ 7.705.085,05
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	1,56	2,28	1,30
Severely injured	0,93	1,35	0,77
Slightly injured	0,35	0,51	0,29
Total	2,84	4,13	2,35
Average	3,11		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (3,11) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: RW 35 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre + edge line	€ 47.623.680,00	€ 26.881.920,00	€ 32.292.000,00	€ 42.400.800,00	€ 37.440.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 4.936.013,26	€ 3.539.866,85	€ 2.639.989,30		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,10	0,18	0,15	0,12	0,13
Severely injured	0,07	0,13	0,11	0,08	0,09
Slightly injured	0,06	0,10	0,08	0,06	0,07
Total	0,23	0,41	0,34	0,26	0,30
Average	0,31				

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years.

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre + edge line	€ 47.623.680,00	€ 26.881.920,00	€ 32.292.000,00	€ 42.400.800,00	€ 37.440.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 41.956.112,71	€ 22.655.147,84	€ 9.700.425,80		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,88	1,56	1,30	0,99	1,12
Severely injured	0,48	0,84	0,70	0,53	0,61
Slightly injured	0,20	0,36	0,30	0,23	0,26
Total	1,56	2,76	2,30	1,75	1,98
Average	2,07				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (2,07) indicates that the benefits are higher than the investment costs of the measure.

3.8. France

3.8.1. Current situation

3.8.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	46600	42200	88800
Primary road	26500	13500	40000
Source: WP1 survey			

3.8.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	22.5	15
Primary road	18/22.5	12/15
Note : Non motorway dual carriageways" - centre line: 15cm, edge line: 22,5 cm; ** "Single carriageways" - centre line: 12 cm, edge line: 18 cm		
Source: WP1 survey		

3.8.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	100/130	100/130
Source: WP1 survey		

3.8.2. Road marking measures to be calculated

French ***motorways*** already meet the visibility criteria for R_L (150), Qd (100/130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200/300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for Qd it is unclear how many motorways meet 100 or 130 $mcd*m^{-2}*lx^{-1}$. Therefore, it is assumed that Qd is currently equal to the lowest value of 100 $mcd*m^{-2}*lx^{-1}$ for the entire motorway network. Additionally, RW 35 is currently very little used are very little used on motorways. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 22.5 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 22.5 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 22.5 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 22.5 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 22.5 cm for edge lines

- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 22.5 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 22.5 cm for edge lines

French ***primary roads*** already meet the visibility criteria for R_L (150) and Qd (100/130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. Furthermore, RW 35 is currently very little used are very little used on primary roads. However, for Qd it is unclear how many primary roads meet 100 or 130 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 100 mcd*m^{-2}*lx^{-1} for the entire primary road network.

Furthermore, for the marking widths it is unclear how many primary roads meet 12/15 cm for centre lines and 18/22.5 cm for edge lines. Therefore, it is assumed that the width is currently equal to the lowest width value provided for centre and edge lines for the entire primary road network. As a result, the marking widths on the primary road network of 12 cm for centre lines and 18 cm for edge lines are currently higher than or already meet the criteria set in the study namely 12 cm for edge lines and 12 cm for centre lines.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines

3.8.3. Input values for social cost-benefit analysis

3.8.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.944.662,00	3.084.533,45
Serious injury	368.029,00	385.510,38
Slight injury	14.070,00	14.738,33
The average harmonised inflation of France in 2022: 4.75% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.8.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	65	59
	Seriously injured	295	154
	Slightly injured	528	223
Night-time: wet	Fatally injured	18	14
	Seriously injured	61	42
	Slightly injured	247	116
Day-time: dry	Fatally injured	170	75
	Seriously injured	575	204
	Slightly injured	838	321

3.8.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
18 cm	€ 1.831,68	€ 1.033,92	€ 1.242,00	€ 1.630,80	€ 1.440,00
22,5 cm	€ 2.289,60	€ 1.292,40	€ 1.552,50	€ 2.038,50	€ 1.800,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
18 cm	€ 851,04	€ 584,10	€ 1.026,00
22,5 cm	€ 1.063,80	€ 730,13	€ 1.282,50

3.8.4. Social cost-benefit analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 22.5 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 29.928.240,00	€ 20.540.850,00	€ 36.081.000,00
22,5 cm edge line	€ 49.573.080,00	€ 34.024.058,00	€ 59.764.500,00
Total	€ 79.501.320,00	€ 54.564.908,00	€ 95.845.500,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 200.494.674,25	€ 113.725.562,10	€ 7.781.838,24
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2,52	3,67	2,09
Severely injured	1,43	2,08	1,19
Slightly injured	0,10	0,14	0,08
Total	4,05	5,90	3,36
Average		4,44	

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (4,44) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 22.5 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 64.414.080,00	€ 36.359.520,00	€ 43.677.000,00	€ 57.349.800,00	€ 50.640.000,00
22,5 cm edge line	€ 106.695.360,00	€ 60.225.840,00	€ 72.346.500,00	€ 94.994.100,00	€ 83.880.000,00
Total	€ 171.109.440,00	€ 96.585.360,00	€ 116.023.500,00	€ 152.343.900,00	€ 134.520.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 200.494.674,25	€ 113.725.562,10	€ 7.781.838,24		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,17	2,08	1,73	1,32	1,49
Severely injured	0,66	1,18	0,98	0,75	0,85
Slightly injured	0,05	0,08	0,07	0,05	0,06
Total	1,88	3,33	2,78	2,11	2,39
Average					

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (2,50) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: RW 35 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Motorways: RW 50 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 64.414.080,00	€ 36.359.520,00	€ 43.677.000,00	€ 57.349.800,00	€ 50.640.000,00
22,5 cm edge line	€ 106.695.360,00	€ 60.225.840,00	€ 72.346.500,00	€ 94.994.100,00	€ 83.880.000,00
Total	€ 171.109.440,00	€ 96.585.360,00	€ 116.023.500,00	€ 152.343.900,00	€ 134.520.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 55.521.602,10	€ 23.516.133,18	€ 3.640.367,51		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,32	0,57	0,48	0,36	0,41
Severely injured	0,14	0,24	0,20	0,15	0,17
Slightly injured	0,02	0,04	0,03	0,02	0,03
Total	0,48	0,86	0,71	0,54	0,61
Average			0,64		

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years.

- **Motorways: Qd 130 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.

- **Motorways: Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 22.5 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 64.414.080,00	€ 36.359.520,00	€ 43.677.000,00	€ 57.349.800,00	€ 50.640.000,00
22,5 cm edge line	€ 106.695.360,00	€ 60.225.840,00	€ 72.346.500,00	€ 94.994.100,00	€ 83.880.000,00
Total	€ 171.109.440,00	€ 96.585.360,00	€ 116.023.500,00	€ 152.343.900,00	€ 134.520.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 524.370.686,50	€ 221.668.468,50	€ 12.350.720,54		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	3,06	5,43	4,52	3,44	3,90
Severely injured	1,30	2,30	1,91	1,46	1,65
Slightly injured	0,07	0,13	0,11	0,08	0,09
Total	4,43	7,85	6,54	4,98	5,64
Average			5,89		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (5,89) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: R_L 200 ($mcd*m^{-2}*lx^{-1}$)with 12 cm for centre lines and 18 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm centre line	€ 7.659.360,00	€ 5.256.900,00	€ 9.234.000,00
18 cm edge line	€ 22.552.560,00	€ 15.478.650,00	€ 27.189.000,00
Total	€ 30.211.920,00	€ 20.735.550,00	€ 36.423.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 181.987.473,55	€ 59.368.598,52	€ 3.286.647,59
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	6,02	8,78	5,00
Severely injured	1,97	2,86	1,63
Slightly injured	0,11	0,16	0,09
Total	8,10	11,80	6,72
Average		8,87	

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (8,87) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: RW 35 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre line	€ 16.485.120,00	€ 9.305.280,00	€ 11.178.000,00	€ 14.677.200,00	€ 12.960.000,00
18 cm edge line	€ 48.539.520,00	€ 27.398.880,00	€ 32.913.000,00	€ 43.216.200,00	€ 38.160.000,00
Total	€ 65.024.640,00	€ 36.704.160,00	€ 44.091.000,00	€ 57.893.400,00	€ 51.120.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 43.183.468,30	€ 16.191.435,96	€ 1.709.646,28		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,66	1,18	0,98	0,75	0,84
Severely injured	0,25	0,44	0,37	0,28	0,32
Slightly injured	0,03	0,05	0,04	0,03	0,03
Total	0,94	1,66	1,39	1,06	1,19
Average	1,25				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure) and thermoplastic (structure). thermoplastic (flatline). Paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (1,25) indicates that the benefits are higher than the investment costs of the measure. This is the case for all materials except for paint (flatline).

- **Primary roads: Qd 130 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre line	€ 16.485.120,00	€ 9.305.280,00	€ 11.178.000,00	€ 14.677.200,00	€ 12.960.000,00
18 cm edge line	€ 48.539.520,00	€ 27.398.880,00	€ 32.913.000,00	€ 32.913.000,00	€ 38.160.000,00
Total	€ 65.024.640,00	€ 36.704.160,00	€ 44.091.000,00	€ 47.590.200,00	€ 51.120.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 231.340.008,75	€ 78.644.117,52	€ 4.731.003,93		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	3,56	6,30	5,25	4,86	4,53
Severely injured	1,21	2,14	1,78	1,65	1,54
Slightly injured	0,07	0,13	0,11	0,10	0,09
Total	4,84	8,57	7,14	6,61	6,16
Average			6,66		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (flatline), thermoplastic (structure) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (6,66) indicates that the benefits are higher than the investment costs of the measure.

3.9. Germany

3.9.1. Current situation

3.9.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	43333	21667	65000
Primary road	73333	36667	110000
Source: WP1 survey			

3.9.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15/30	15
Primary road	12/25	12
Note : Motorways: left edge line 15 or 30 cm, right edge line or dashed right edge line 30 cm, dashed centre line 15 cm. National Roads: edge lines 12 cm, edge lines to separate hard shoulder/bus stops or dashed right edge line 25 cm, dashed centre marking 12 cm.		
Source: WP1 survey		

3.9.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200/300	200/300
Night-time: wet (RW)	50/75	50/75
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.9.2. Road marking measures to be calculated

German ***motorways*** already meet or have higher visibility criteria in place for R_L (200/300), RW (50/75) and Qd (160) $mcd*m^{-2}*lx^{-1}$. However, for R_L it is unclear how many motorways meet 200 or 300. Therefore, it is assumed that R_L is currently equal to the lowest value of 200 $mcd*m^{-2}*lx^{-1}$ for the entire motorway network. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 15 cm for edge lines or already meet the criteria set in the study namely 15 cm. However, for the edge line marking widths it is unclear how many motorways currently meet the 30 cm criterion. Therefore, it is assumed that the width is currently equal to the lowest width value provided for edge lines. As a result, the marking widths already meet the 15 cm criterion for edge lines set in the study but do not meet the 20 cm criterion.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- RL 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RL 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

German ***primary roads*** already meet or have higher visibility criteria in place for R_L RW and Qd than the common defined visibility criteria. Furthermore, these primary roads also meet the common minimal width levels of 12 cm for edge and centre lines. Therefore, there is no need to calculate a break-even cost-benefit analysis.

3.9.3. Input values for social cost-benefit analysis

3.9.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.177.194,00	1.255.948,28
Serious injury	119.480,00	127.473,21
Slight injury	4.954,00	5.285,42
The average harmonised inflation of Germany in 2022: 6.69% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.9.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	102	No crash and injury data available
	Seriously injured	2027	
	Slightly injured	5872	
Night-time: wet	Fatally injured	2	
	Seriously injured	34	
	Slightly injured	99	
Day-time: dry	Fatally injured	187	
	Seriously injured	3905	
	Slightly injured	9358	

3.9.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.9.4. Social cost-benefit analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 15.366.236,40	€ 10.546.412,25	€ 18.525.285,00
20 cm edge line	€ 40.975.684,80	€ 28.123.117,00	€ 49.399.620,00
Total	€ 56.341.921,20	€ 38.669.529,25	€ 67.924.905,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 128.106.724,56	€ 258.388.196,67	€ 31.035.986,24
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2,27	3,31	1,89
Severely injured	4,59	6,68	3,80
Slightly injured	0,55	0,80	0,46
Total	7,41	10,80	6,15
Average	8,12		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (8,12) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 33.072.508,80	€ 18.668.287,20	€ 22.425.345,00	€ 29.445.453,00	€ 26.000.400,00
20 cm edge line	€ 88.191.321,60	€ 49.780.950,40	€ 59.799.540,00	€ 78.519.396,00	€ 69.332.800,00
Total	€ 121.263.830,40	€ 68.449.237,60	€ 82.224.885,00	€ 107.964.849,00	€ 95.333.200,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 128.106.724,56	€ 258.388.196,67	€ 31.035.986,24		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,06	1,87	1,56	1,19	1,34
Severely injured	2,13	3,77	3,14	2,39	2,71
Slightly injured	0,26	0,45	0,38	0,29	0,33
Total	3,44	6,10	5,08	3,87	4,38
Average	4,57				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (4,57) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: RW 50 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 33.072.508,80	€ 18.668.287,20	€ 22.425.345,00	€ 29.445.453,00	€ 26.000.400,00
20 cm edge line	€ 88.191.321,60	€ 49.780.950,40	€ 59.799.540,00	€ 78.519.396,00	€ 69.332.800,00
Total	€ 121.263.830,40	€ 68.449.237,60	€ 82.224.885,00	€ 107.964.849,00	€ 95.333.200,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.511.896,56	€ 4.334.089,14	€ 523.256,58		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,02	0,04	0,03	0,02	0,03
Severely injured	0,04	0,06	0,05	0,04	0,05
Slightly injured	0,00	0,01	0,01	0,00	0,01
Total	0,06	0,11	0,09	0,07	0,08
Average	0,08				

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years.

- **Motorways: Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 33.072.508,80	€ 18.668.287,20	€ 22.425.345,00	€ 29.445.453,00	€ 26.000.400,00
20 cm edge line	€ 88.191.321,60	€ 49.780.950,40	€ 59.799.540,00	€ 78.519.396,00	€ 69.332.800,00
Total	€ 121.263.830,40	€ 68.449.237,60	€ 82.224.885,00	€ 107.964.849,00	€ 95.333.200,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 234.862.328,36	€ 497.782.885,05	€ 49.460.960,36		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,94	3,43	2,86	2,18	2,46
Severely injured	4,10	7,27	6,05	4,61	5,22
Slightly injured	0,41	0,72	0,60	0,46	0,52
Total	6,45	11,43	9,51	7,24	8,20
Average	8,57				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (8,57) indicates that the benefits are higher than the investment costs of the measure.

3.10. Hungary

3.10.1. Current situation

3.10.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	5036	881	5917
Primary road	15674	2612	18286
Source: WP1 survey			

3.10.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15/20	12/15
Primary road	15	12
Source: WP1 survey		

3.10.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	150
Night-time: wet (RW)	75	50
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.10.2. Road marking measures to be calculated

Hungarian ***motorways*** already meet or have higher visibility criteria in place for R_L (200), RW (75) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge lines meet a width of 15 or 20 cm and how many centre lines meet a width of 12 or 15 cm.

Therefore, it is assumed that the *edge line* width for the entire motorway network is currently equal to the lowest value provided namely 15 cm. This value is equal to the recommended width of 15 cm but is lower than the recommended width of 20 cm. For the current *centre line* width, we assume that the entire motorway network is currently equal to the lowest value provided namely 12 cm. This value is lower than the recommended width of 15 cm.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

- RW 75 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- RW 75 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

Hungarian ***primary roads*** already meet or have higher visibility criteria in place for R_L (150), RW (55) and Qd (130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200 and Qd 160 mcd*m^{-2}*lx^{-1}. Furthermore, the marking widths on the primary road network of 12 cm for centre lines and 15 cm for edge lines are currently higher than or already meet the criteria set in the study namely 12 cm for edge lines and 12 cm for centre lines.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 15 cm for edge lines

3.10.3. Input values for social cost-benefit analysis

3.10.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.147.976,00	2.342.797,42
Serious injury	501.194,00	546.652,30
Slight injury	553,00	603,16
The average harmonised inflation of Hungary in 2022: 9.07% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.10.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	6	0
	Seriously injured	60	6
	Slightly injured	159	26
Night-time: wet	Fatally injured	0	0
	Seriously injured	9	2
	Slightly injured	26	9
Day-time: dry	Fatally injured	14	6
	Seriously injured	139	29
	Slightly injured	418	113

3.10.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 $mcd*m^{-2}*lx^{-1}$					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 $mcd*m^{-2}*lx^{-1}$			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.10.4. Social cost-benefit analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 624.805,20	€ 428.826,75	€ 753.255,00
15 cm edge line	€ 3.571.531,20	€ 2.451.273,00	€ 4.305.780,00
Total	€ 4.196.336,40	€ 2.880.099,75	€ 5.059.035,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 14.056.784,52	€ 32.799.138,00	€ 95.902,44
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	3,35	4,88	2,78
Severely injured	7,82	11,39	6,48
Slightly injured	0,02	0,03	0,02
Total	11,19	16,30	9,28
Average	12,26		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (12,26) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 624.805,20	€ 428.826,75	€ 753.255,00
20 cm edge line	€ 4.762.041,60	€ 3.268.364,00	€ 5.741.040,00
Total	€ 5.386.846,80	€ 3.697.190,75	€ 6.494.295,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 14.056.784,52	€ 32.799.138,00	€ 95.902,44
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2,61	3,80	2,16
Severely injured	6,09	8,87	5,05
Slightly injured	0,02	0,03	0,01
Total	8,72	12,70	7,23
Average	9,55		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (9,55) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.344.758,40	€ 759.069,60	€ 911.835,00	€ 1.197.279,00	€ 1.057.200,00
15 cm edge line	€ 7.686.950,40	€ 4.339.017,60	€ 5.212.260,00	€ 6.843.924,00	€ 6.043.200,00
Total	€ 9.031.708,80	€ 5.098.087,20	€ 6.124.095,00	€ 8.041.203,00	€ 7.100.400,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 14.056.784,52	€ 32.799.138,00	€ 95.902,44		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,56	2,76	2,30	1,75	1,98
Severely injured	3,63	6,43	5,36	4,08	4,62
Slightly injured	0,01	0,02	0,02	0,01	0,01
Total	5,20	9,21	7,67	5,84	6,61
Average	6,91				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (6,91) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 300 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.344.758,40	€ 759.069,60	€ 911.835,00	€ 1.197.279,00	€ 1.057.200,00
20 cm edge line	€ 10.249.267,20	€ 5.785.356,80	€ 6.949.680,00	€ 9.125.232,00	€ 8.057.600,00
Total	€ 11.594.025,60	€ 6.544.426,40	€ 7.861.515,00	€ 10.322.511,00	€ 9.114.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 14.056.784,52	€ 32.799.138,00	€ 95.902,44		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,21	2,15	1,79	1,36	1,54
Severely injured	2,83	5,01	4,17	3,18	3,60
Slightly injured	0,01	0,01	0,01	0,01	0,01
Total	4,05	7,17	5,97	4,55	5,15
Average	5,38				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (5,38) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: RW 75 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 15 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 75 mcd*m^{-2}*lx^{-1}.

- **Motorways: RW 75 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 75 mcd*m^{-2}*lx^{-1}.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 15 cm for edge lines**

- Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.344.758,40	€ 759.069,60	€ 911.835,00	€ 1.197.279,00	€ 1.057.200,00
15 cm edge line	€ 7.686.950,40	€ 4.339.017,60	€ 5.212.260,00	€ 6.843.924,00	€ 6.043.200,00
Total	€ 9.031.708,80	€ 5.098.087,20	€ 6.124.095,00	€ 8.041.203,00	€ 7.100.400,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 32.799.163,88	€ 75.984.669,70	€ 252.120,88		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	3,63	6,43	5,36	4,08	4,62
Severely injured	8,41	14,90	12,41	9,45	10,70
Slightly injured	0,03	0,05	0,04	0,03	0,04
Total	12,07	21,39	17,80	13,56	15,36
Average	16,04				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (16,04) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.344.758,40	€ 759.069,60	€ 911.835,00	€ 1.197.279,00	€ 1.057.200,00
20 cm edge line	€ 10.249.267,20	€ 5.785.356,80	€ 6.949.680,00	€ 9.125.232,00	€ 8.057.600,00
Total	€ 11.594.025,60	€ 6.544.426,40	€ 7.861.515,00	€ 10.322.511,00	€ 9.114.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 32.799.163,88	€ 75.984.669,70	€ 252.120,88		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	2,83	5,01	4,17	3,18	3,60
Severely injured	6,55	11,61	9,67	7,36	8,34
Slightly injured	0,02	0,04	0,03	0,02	0,03
Total	9,40	16,66	13,87	10,56	11,96
Average	12,49				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (12,49) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: R_L 200 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm centre line	€ 1.481.944,32	€ 1.017.112,80	€ 1.786.608,00
15 cm edge line	€ 11.116.000,80	€ 7.629.319,50	€ 13.401.270,00
Total	€ 12.597.945,12	€ 8.646.432,30	€ 15.187.878,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 0,00	€ 3.279.913,80	€ 15.682,16
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	0,00	0,00	0,00
Severely injured	0,26	0,38	0,22
Slightly injured	0,00	0,00	0,00
Total	0,26	0,38	0,22
Average	0,29		

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. This result is caused by the fact that from 2017-2020 the single-vehicle crashes on primary roads did not result in fatally injured. Therefore, the actual cost-effectiveness of the measures is expected to be higher than presented.

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre line	€ 3.189.565,44	€ 1.800.399,36	€ 2.162.736,00	€ 2.839.766,40	€ 2.507.520,00
15 cm edge line	€ 23.924.793,60	€ 13.504.718,40	€ 16.222.590,00	€ 21.300.966,00	€ 18.808.800,00
Total	€ 27.114.359,04	€ 15.305.117,76	€ 18.385.326,00	€ 24.140.732,40	€ 21.316.320,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 14.056.784,52	€ 15.852.916,70	€ 68.157,08		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,52	0,92	0,76	0,58	0,66
Severely injured	0,58	1,04	0,86	0,66	0,74
Slightly injured	0,00	0,00	0,00	0,00	0,00
Total	1,11	1,96	1,63	1,24	1,41
Average	1,47				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (1,47) indicates that the benefits are higher than the investment costs of the measure.

3.11. Iceland

3.11.1. Current situation

3.11.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No roads classified as motorways		
Primary road	6620	4490	11110
Source: WP1 survey			

3.11.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	No roads classified as motorways	
Primary road	10	10
Source: WP1 survey		

3.11.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	No roads classified as motorways	150
Night-time: wet (RW)		Not requested
Day-time: dry (Qd)		130
Source: WP1 survey		

3.11.2. Road marking measures to be calculated

Iceland has no motorways. Therefore, the social cost-benefit analysis is only calculated for certain values for primary roads.

Icelandic ***primary roads*** already have visibility criteria in place for R_L (150) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200, RW 35/50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the primary road network of 10 cm for centre lines and 10 cm for edge lines are currently lower than the criteria set in the study namely 12 cm for edge lines and centre lines.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ 12 cm for centre lines and 12 cm for edge lines

3.11.3. Input values for social cost-benefit analysis

3.11.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.861.281,00	2.995.475,08
Serious injury	364.914,00	382.028,47
Slight injury	71.742,00	75.106,70
The average harmonised inflation of Iceland in 2022: 4.69% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.11.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	
	Seriously injured		
	Slightly injured		
Night-time: wet	Fatally injured		
	Seriously injured		
	Slightly injured		
Day-time: dry	Fatally injured		
	Seriously injured		
	Slightly injured		

3.11.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00

3.11.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated as there is no crash and injury data available for the target crashes in the CARE database.

3.12. Ireland

3.12.1. Current situation

3.12.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	1.888	250	2138
Primary road	4.298	4.000	8298
Source: WP1 survey			

3.12.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15	10
Primary road	15	15
Source: WP1 survey		

3.12.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	200	200
Source: WP1 survey		

3.12.2. Road marking measures to be calculated

Irish ***motorways*** already meet the visibility criteria for R_L (150), R_L (200), RW (50) and Qd (100/130/160) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 300 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 10 cm for centre lines and 15 cm for edge lines are currently lower than he criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- Qd 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

Irish ***primary roads*** already meet the visibility criteria for R_L (150), R_L 200, RW (50) and Qd (100/130/160) mcd*m^{-2}*lx^{-1}. Furthermore, the marking widths on the primary road network of 15 cm for centre and edge lines are currently higher than the criteria set in the study namely 12 cm for edge and centre lines.

Therefore, there is no need to calculate a social cost-benefit analysis for primary roads.

3.12.3. Input values for social cost-benefit analysis

3.12.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.965.163,00	2.153.818,65
Serious injury	225.511,00	247.160,06
Slight injury	20.860,00	22.862,56
The average harmonised inflation of Ireland in 2022: 9.60% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.12.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	
	Seriously injured		
	Slightly injured		
Night-time: wet	Fatally injured		
	Seriously injured		
	Slightly injured		
Day-time: dry	Fatally injured		
	Seriously injured		
	Slightly injured		

3.12.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00

3.12.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated since there is no crash and injury data available for the target crashes in the CARE database.

3.13. Italy

3.13.1. Current situation

3.13.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.13.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	15
Primary road	12/25	15
Source: WP1 survey		

3.13.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	Not requested
Night-time: wet (RW)	50	Not requested
Day-time: dry (Qd)	130	Not requested
Source: WP1 survey		

3.13.2. Road marking measures to be calculated

Italian ***motorways*** already meet the visibility criteria for R_L (150), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200/300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 25 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 25 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 25 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 25 cm for edge lines

Italy has no set requirements for ***primary roads*** with respect to road marking visibility. The current centre line width of 15 cm is higher than the recommended width of 15 cm.

However, for the marking widths it is unclear how many edge lines meet a width of 12 or 25 cm. Therefore, it is assumed that the *edge line* width for the entire primary road network is currently equal to the lowest value provided namely 12 cm. This value is equal to the recommended width of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- R_L 150 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- Qd 100 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines

3.13.3. Input values for social cost-benefit analysis

3.13.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.615.566,00	1.717.831,33
Serious injury	211.860,00	225.270,74
Slight injury	18.245,00	19.399,91
The average harmonised inflation of Italy in 2022: 6.33% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.13.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	
	Seriously injured		
	Slightly injured		
Night-time: wet	Fatally injured		
	Seriously injured		
	Slightly injured		
Day-time: dry	Fatally injured		
	Seriously injured		
	Slightly injured		

3.13.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
25 cm	€ 2.544,00	€ 1.436,00	€ 1.725,00	€ 2.265,00	€ 2.000,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
25 cm	€ 1.182,00	€ 811,25	€ 1.425,00

3.13.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads. Furthermore, there is no crash and injury data available for the target crashes in the CARE database.

3.14. Latvia

3.14.1. Current situation

3.14.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No roads classified as motorways		
Primary road	No data delivered		
Source: WP1 survey			

3.14.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	No roads classified as motorways	
Primary road	10/15/20	10/15/20
Source: WP1 survey		

3.14.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	No roads classified as motorways	150
Night-time: wet (RW)		50
Day-time: dry (Qd)		100
Source: WP1 survey		

3.14.2. Road marking measures to be calculated

Latvia has no motorways. Therefore, the social cost-benefit analysis is only calculated for certain values for primary roads.

Latvian ***primary roads*** already meet the visibility criteria for R_L (150), RW (50) and Qd (100) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200 and Qd 130/160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge and centre lines meet a width of 10, 15 or 20 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the middle value provided namely 15 cm. This value is higher than the recommended width of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- Qd 130 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines

3.14.3. Input values for social cost-benefit analysis

3.14.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.141.935,00	1.219.358,19
Serious injury	28.205,00	30.117,30
Slight injury	296,00	316,07
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Latvia Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.14.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	3
	Seriously injured		31
	Slightly injured		166
Night-time: wet	Fatally injured		2
	Seriously injured		5
	Slightly injured		34
Day-time: dry	Fatally injured		6
	Seriously injured		43
	Slightly injured		223

3.14.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 $mcd*m^{-2}*lx^{-1}$					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00

R_L 200 / Qd 160 $mcd*m^{-2}*lx^{-1}$			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00

3.14.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on primary roads.

3.15. Lithuania

3.15.1. Current situation

3.15.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	1720	860	2580
Primary road	2892	1446	4338
Source: WP1 survey			

3.15.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	15
Primary road	25	12
Source: WP1 survey		

3.15.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.15.2. Road marking measures to be calculated

Lithuanian ***motorways*** already meet the visibility criteria for R_L (200), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 30 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines

Lithuanian ***primary roads*** already meet the visibility criteria in place for R_L (200), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criterion of Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the primary network of 12 cm for centre lines and 25 cm for edge lines are currently higher than or equal to the criteria set in the study namely 12 cm for edge lines and 12 cm for centre lines.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measure:

- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 25 cm for edge lines

3.15.3. Input values for social cost-benefit analysis

3.15.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	988.981,00	1.056.033,91
Serious injury	89.804,00	95.892,71
Slight injury	Not available	Not available

The average harmonised inflation of Europe in 2022: 6.78%*

*Note: European average used since there is no specific HICP value available for Lithuania

Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)

3.15.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	1	No crash and injury data available
	Seriously injured	11	
	Slightly injured	39	
Night-time: wet	Fatally injured	2	
	Seriously injured	1	
	Slightly injured	11	
Day-time: dry	Fatally injured	2	
	Seriously injured	11	
	Slightly injured	57	

3.15.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
25 cm	€ 2.544,00	€ 1.436,00	€ 1.725,00	€ 2.265,00	€ 2.000,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

3.15.4. Social cost-benefit analysis results

- **Motorways: R_L 300 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.312.704,00	€ 740.976,00	€ 890.100,00	€ 1.168.740,00	€ 1.032.000,00
30 cm edge line	€ 5.250.816,00	€ 2.963.904,00	€ 3.560.400,00	€ 4.674.960,00	€ 4.128.000,00
Total	€ 6.563.520,00	€ 3.704.880,00	€ 4.450.500,00	€ 5.843.700,00	€ 5.160.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.056.033,91	€ 1.054.819,81			
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,16	0,29	0,24	0,18	0,20
Severely injured	0,16	0,28	0,24	0,18	0,20
Slightly injured					
Total	0,32	0,57	0,47	0,36	0,41
Average			0,43		

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. However, the benefits could not be calculated for slightly injured because there is no unit cost for slightly injured road users available for Lithuania. Therefore, the actual cost-effectiveness of the measures is expected to be higher than presented.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.312.704,00	€ 740.976,00	€ 890.100,00	€ 1.168.740,00	€ 1.032.000,00
30 cm edge line	€ 5.250.816,00	€ 2.963.904,00	€ 3.560.400,00	€ 4.674.960,00	€ 4.128.000,00
Total	€ 6.563.520,00	€ 3.704.880,00	€ 4.450.500,00	€ 5.843.700,00	€ 5.160.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.112.067,82	€ 1.054.819,81			
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,32	0,57	0,47	0,36	0,41
Severely injured	0,16	0,28	0,24	0,18	0,20
Slightly injured	0,00	0,00	0,00	0,00	0,00
Total	0,48	0,85	0,71	0,54	0,61
Average			0,64		

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. However, the benefits could not be calculated for slightly injured because there is no unit cost for slightly injured road users available for Lithuania. Therefore, the actual cost-effectiveness of the measures is expected to be higher than presented.

- **Primary roads: Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 25 cm for edge lines**

  Currently, the social cost-benefit analysis cannot be calculated as there is no crash and injury data available for the target crashes on primary roads in the CARE database.

3.16. Luxembourg

3.16.1. Current situation

3.16.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	1000	330	1330
Primary road	No data delivered		
Source: WP1 survey			

3.16.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	22.5	15
Primary road	12	12
Source: WP1 survey		

3.16.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (RL)	300	200
Night-time: wet (RW)	75	50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.16.2. Road marking measures to be calculated

The road markings on motorways and primary roads in Luxembourg already meet the visibility and width levels recommended by the study or have higher visibility and width levels in place.

As a result, there is no need to calculate a social cost-benefit analysis.

3.17. Netherlands

3.17.1. Current situation

3.17.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	11058	2146	13204
Primary road	8846	1718	10564
Source: WP1 survey			

3.17.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	15
Primary road	15/20	15
Source: WP1 survey		

3.17.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	100	100
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.17.2. Road marking measures to be calculated

Dutch ***motorways*** already meet the visibility criteria for R_L (100), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 150/200/300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 20 cm for edge lines already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 150 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

Dutch ***primary roads*** already meet the visibility criteria for R_L (100), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 150/200, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the primary road network of 15 cm for centre lines and 15/20 cm for edge lines are higher than the criteria set in the study namely 12 cm for edge lines and centre lines.

However, for the marking widths it is unclear how many edge lines meet a width of 15 or 20 cm. Therefore, it is assumed that the *edge line* width for the entire primary road network is currently equal to the lowest value provided namely 15 cm. This value is higher than the recommended width of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 150 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

3.17.3. Input values for social cost-benefit analysis

3.17.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.504.928,00	2.744.900,10
Serious injury	269.149,00	294.933,47
Slight injury	6.031,00	6.608,77
The average harmonised inflation of The Netherlands in 2022: 9.58% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.17.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	10	No crash and injury data available
	Seriously injured	313	
	Slightly injured	117	
Night-time: wet	Fatally injured	7	
	Seriously injured	79	
	Slightly injured	44	
Day-time: dry	Fatally injured	43	
	Seriously injured	572	
	Slightly injured	206	

3.17.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.17.4. Social cost-benefit analysis results

- **Motorways: R_L 150 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for R_L 150 mcd*m^{-2}*lx^{-1}.

- **Motorways: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 1.521.943,20	€ 1.044.565,50	€ 1.834.830,00
20 cm edge line	€ 10.456.444,80	€ 7.176.642,00	€ 12.606.120,00
Total	€ 11.978.388,00	€ 8.221.207,50	€ 14.440.950,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 27.449.001,00	€ 92.314.176,11	€ 773.226,09
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2,29	3,34	1,90
Severely injured	7,71	11,23	6,39
Slightly injured	0,06	0,09	0,05
Total	10,06	14,66	8,35
Average	11,02		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by paint (flatline) and thermoplastic (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (11,02) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 3.275.654,40	€ 1.848.993,60	€ 2.221.110,00	€ 2.916.414,00	€ 2.575.200,00
20 cm edge line	€ 22.505.241,60	€ 12.703.430,40	€ 15.260.040,00	€ 20.037.096,00	€ 17.692.800,00
Total	€ 25.780.896,00	€ 14.552.424,00	€ 17.481.150,00	€ 22.953.510,00	€ 20.268.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 27.449.001,00	€ 92.314.176,11	€ 773.226,09		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,06	1,89	1,57	1,20	1,35
Severely injured	3,58	6,34	5,28	4,02	4,55
Slightly injured	0,03	0,05	0,04	0,03	0,04
Total	4,68	8,28	6,90	5,25	5,95
Average	6,21				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (6,21) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: RW 50 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 3.275.654,40	€ 1.848.993,60	€ 2.221.110,00	€ 2.916.414,00	€ 2.575.200,00
20 cm edge line	€ 22.505.241,60	€ 12.703.430,40	€ 15.260.040,00	€ 20.037.096,00	€ 17.692.800,00
Total	€ 25.780.896,00	€ 14.552.424,00	€ 17.481.150,00	€ 22.953.510,00	€ 20.268.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 19.214.300,70	€ 23.299.744,13	€ 290.785,88		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,75	1,32	1,10	0,84	0,95
Severely injured	0,90	1,60	1,33	1,02	1,15
Slightly injured	0,01	0,02	0,02	0,01	0,01
Total	1,66	2,94	2,45	1,86	2,11
Average	2,21				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (2,21) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 3.275.654,40	€ 1.848.993,60	€ 2.221.110,00	€ 2.916.414,00	€ 2.575.200,00
20 cm edge line	€ 22.505.241,60	€ 12.703.430,40	€ 15.260.040,00	€ 20.037.096,00	€ 17.692.800,00
Total	€ 25.780.896,00	€ 14.552.424,00	€ 17.481.150,00	€ 22.953.510,00	€ 20.268.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 118.030.704,30	€ 168.701.944,84	€ 1.361.406,62		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	4,58	8,11	6,75	5,14	5,82
Severely injured	6,54	11,59	9,65	7,35	8,32
Slightly injured	0,05	0,09	0,08	0,06	0,07
Total	11,17	19,80	16,48	12,55	14,21
Average	14,84				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (14,84) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads**

  Currently, the social cost-benefit analysis cannot be calculated as there is no crash and injury data available for the target crashes on primary roads in the CARE database.

3.18. Norway

3.18.1. Current situation

3.18.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	4000	500	4500
Primary road	8000	4000	12000
Source: WP1 survey			

3.18.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	15
Primary road	10/15	10/15
Source: WP1 survey		

3.18.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.18.2. Road marking measures to be calculated

Norwegian ***motorways*** already meet the visibility criteria for R_L (150), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200/300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 30 cm for edge lines already meet or are higher than the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines

Norwegian ***primary roads*** already meet the visibility criteria for R_L (150), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge and centre lines meet a width of 10 or 15 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. This value is lower than the recommended width of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines

3.18.3. Input values for social cost-benefit analysis

3.18.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.690.394,00	2.872.802,71
Serious injury	845.812,00	903.158,05
Slight injury	52.970,00	56.561,37
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Norway Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.18.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	No crash and injury data available	
	Seriously injured		
	Slightly injured		
Night-time: wet	Fatally injured		
	Seriously injured		
	Slightly injured		
Day-time: dry	Fatally injured		
	Seriously injured		
	Slightly injured		

3.18.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
30 cm	€ 1.418,40	€ 973,50	€ 1.710,00

3.18.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated as there is no crash and injury data available for the target crashes on motorways and primary roads in the CARE database.

3.19. Poland

3.19.1. Current situation

3.19.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.19.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	24	12/24
Primary road	24	12/24
Source: WP1 survey		

3.19.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	250	250
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	130/160	130/160
Source: WP1 survey		

3.19.2. Road marking measures to be calculated

Polish ***motorways*** already meet the visibility criteria for R_L (250), RW (50) and Qd (130/160) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criterion of R_L 300 $mcd*m^{-2}*lx^{-1}$. However, for Qd it is unclear how many motorways meet 130 or 160 $mcd*m^{-2}*lx^{-1}$. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 $mcd*m^{-2}*lx^{-1}$ for the entire motorway network.

Furthermore, for the marking widths it is unclear how many centre lines meet a width of 12 or 24 cm. Therefore, it is assumed that the *centre line* width for the entire motorway network is currently equal to the lowest value provided namely 12 cm. As a result, the marking width of centre lines on the motorway network does not meet the criterion set in the study namely 15 cm. In addition, the current edge line marking width of 24 cm on motorways is higher than the criterion set in the study namely 15/20 cm for edge lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 24 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 24 cm for edge lines

- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 24 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 24 cm for edge lines

Polish ***primary roads*** already meet the visibility criteria for R_L (250), RW (50) and Qd (130/160) mcd*m^{-2}*lx^{-1}. However, for Qd it is unclear how many motorways meet 130 or 160 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 mcd*m^{-2}*lx^{-1} for the entire motorway network.

Furthermore, the marking widths on the primary road network of 12/24 cm for centre lines and 24 cm for edge lines already meet or are higher than the criteria set in the study namely 12 cm edge and lines. However, for the marking widths it is unclear how many centre lines meet a width of 12 or 24 cm. Therefore, it is assumed that the *centre line* width for the entire primary road network is currently equal to the lowest value provided namely 12 cm. This value is equal to the recommended width of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measure:

- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 24 cm for edge lines

3.19.3. Input values for social cost-benefit analysis

3.19.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	814.504,00	897.827,76
Serious injury	975.074,00	1.074.824,07
Slight injury	11.536,00	12.716,13
The average harmonised inflation of Poland in 2022: 10.23% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.19.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	9	2
	Seriously injured	30	10
	Slightly injured	72	24
Night-time: wet	Fatally injured	1	2
	Seriously injured	10	5
	Slightly injured	24	20
Day-time: dry	Fatally injured	23	11
	Seriously injured	81	34
	Slightly injured	207	102

3.19.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
24 cm	€ 2.442,24	€ 1.378,56	€ 1.656,00	€ 2.174,40	€ 1.920,00

3.19.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads.

3.20. Portugal

3.20.1. Current situation

3.20.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	11940	7110	19050
Primary road	No data delivered		
Source: WP1 survey			

3.20.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	15
Primary road	15	12
Source: WP1 survey		

3.20.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	Not requested	50
Day-time: dry (Qd)	Not requested	160
Source: WP1 survey		

3.20.2. Road marking measures to be calculated

Portuguese ***motorways*** already meet the visibility criterion for R_L (200) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criterion of R_L 300 mcd*m^{-2}*lx^{-1}. Visibility criteria for Qd and RW are not defined. The edge and centre line markings meet the recommended width of 15 cm for centre lines and 20 cm for edge lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 100 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

The road markings on ***primary roads*** in Portugal already meet the visibility and width levels recommended by the study or have higher width levels in place. As a result, there is no need to calculate a social cost-benefit analysis for primary roads.

3.20.3. Input values for social cost-benefit analysis

3.20.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	838.109,00	886.300,27
Serious injury	136.365,00	144.205,99
Slight injury	35.391,00	37.425,98
The average harmonised inflation of Portugal in 2022: 5.75% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.20.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	23	No crash and injury data available
	Seriously injured	51	
	Slightly injured	747	
Night-time: wet	Fatally injured	2	
	Seriously injured	15	
	Slightly injured	441	
Day-time: dry	Fatally injured	43	
	Seriously injured	125	
	Slightly injured	1854	

3.20.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / RL 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

3.20.4. Social cost-benefit analysis results

- **Motorways: R_L 300 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 10.852.704,00	€ 6.125.976,00	€ 7.358.850,00	€ 9.662.490,00	€ 8.532.000,00
20 cm edge line	€ 24.300.288,00	€ 13.716.672,00	€ 16.477.200,00	€ 21.635.280,00	€ 19.104.000,00
Total	€ 35.152.992,00	€ 19.842.648,00	€ 23.836.050,00	€ 31.297.770,00	€ 27.636.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 20.384.906,21	€ 7.354.505,49	€ 27.957.207,06		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,58	1,03	0,86	0,65	0,74
Severely injured	0,21	0,37	0,31	0,23	0,27
Slightly injured	0,80	1,41	1,17	0,89	1,01
Total	1,58	2,81	2,34	1,78	2,02
Average	2,10				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (2,10) indicates that the benefits are higher than the investment costs of the measure.

- **Motorways: RW 35 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Motorways: RW 50 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 10.852.704,00	€ 6.125.976,00	€ 7.358.850,00	€ 9.662.490,00	€ 8.532.000,00
20 cm edge line	€ 24.300.288,00	€ 13.716.672,00	€ 16.477.200,00	€ 21.635.280,00	€ 19.104.000,00
Total	€ 35.152.992,00	€ 19.842.648,00	€ 23.836.050,00	€ 31.297.770,00	€ 27.636.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.772.600,54	€ 2.163.089,85	€ 16.504.857,18		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,05	0,09	0,07	0,06	0,06
Severely injured	0,06	0,11	0,09	0,07	0,08
Slightly injured	0,47	0,83	0,69	0,53	0,60
Total	0,58	1,03	0,86	0,65	0,74
Average	0,77				

According to the comparison of the BCR the only cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline). Coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (0,77) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: Qd 100 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 100 mcd*m^{-2}*lx^{-1}.

- **Motorways: Qd 130 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 10.852.704,00	€ 6.125.976,00	€ 7.358.850,00	€ 9.662.490,00	€ 8.532.000,00
20 cm edge line	€ 24.300.288,00	€ 13.716.672,00	€ 16.477.200,00	€ 21.635.280,00	€ 19.104.000,00
Total	€ 35.152.992,00	€ 19.842.648,00	€ 23.836.050,00	€ 31.297.770,00	€ 27.636.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 38.110.911,61	€ 18.025.748,75	€ 69.387.766,92		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,08	1,92	1,60	1,22	1,38
Severely injured	0,51	0,91	0,76	0,58	0,65
Slightly injured	1,97	3,50	2,91	2,22	2,51
Total	3,57	6,33	5,27	4,01	4,54
Average			4,74		

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the chosen road marking material, the average benefit-cost ratio (4,74) indicates that the benefits are higher than the investment costs of the measure.

3.21. Romania

3.21.1. Current situation

3.21.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	3840	634	4474
Primary road	35480	10644	46124
Source: WP1 survey			

3.21.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	15
Primary road	15	15
Source: WP1 survey		

3.21.1.1. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	75	75
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.21.2. Road marking measures to be calculated

The road markings on motorways and primary roads in Romania already meet the visibility and width levels recommended by the study or have higher visibility and width levels in place. As a result, there is no need to calculate a social cost-benefit analysis.

3.22. Slovakia

3.22.1. Current situation

3.22.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	2100	499	2599
Primary road	1082	268	1350
Source: WP1 survey			

3.22.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	12.5
Primary road	25	12.5
Source: WP1 survey		

3.22.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	35/50	35/50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.22.2. Road marking measures to be calculated

Motorways in Slovakia already meet the visibility criteria for R_L (300), RW (35/50) and Qd (160) $mcd*m^{-2}*lx^{-1}$. However, for RW it is unclear how many motorways meet 35 or 50 $mcd*m^{-2}*lx^{-1}$. Therefore, it is assumed that RW is currently equal to the lowest value of 35 $mcd*m^{-2}*lx^{-1}$ for the entire motorway network.

The current marking width of edge lines on motorways of 25 cm is higher than the recommended values of 15/20 cm. However, the current marking width of centre lines on motorways of 12.5 cm is lower than the recommended value of 15 cm.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 25 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 25 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 25 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 25 cm for edge lines

Primary roads in Slovakia already meet the visibility criteria for R_L (300), RW (35/50) and Qd (160) mcd*m^{-2}*lx^{-1}. However, for RW it is unclear how many primary roads meet 35 or 50 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that RW is currently equal to the lowest value of 35 mcd*m^{-2}*lx^{-1} for the entire primary road network.

The current marking width of edge lines on primary roads of 25 cm is higher than the recommended values of 12 cm. Additionally, the current marking width of centre lines on primary roads of 12.5 cm is higher than the recommended value of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measure:

- RW 50 mcd*m^{-2}*lx^{-1} with 12.5 cm for centre lines and 25 cm for edge lines

3.22.3. Input values for social cost-benefit analysis

3.22.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	652.238,00	715.048,52
Serious injury	141.504,00	155.130,84
Slight injury	20.767,00	22.766,86
The average harmonised inflation of Slovakia in 2022: 9.63% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.22.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	2	No crash and injury data available
	Seriously injured	14	
	Slightly injured	58	
Night-time: wet	Fatally injured	2	
	Seriously injured	9	
	Slightly injured	46	
Day-time: dry	Fatally injured	12	
	Seriously injured	30	
	Slightly injured	111	

3.22.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12,5 cm	€ 1.272,00	€ 718,00	€ 862,50	€ 1.132,50	€ 1.000,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
25 cm	€ 2.544,00	€ 1.436,00	€ 1.725,00	€ 2.265,00	€ 2.000,00

3.22.4. Social cost-benefit analysis results

- **Motorways: R_L 300 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 25 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 761.673,60	€ 429.938,40	€ 516.465,00	€ 678.141,00	€ 598.800,00
25 cm edge line	€ 5.342.400,00	€ 3.015.600,00	€ 3.622.500,00	€ 4.756.500,00	€ 4.200.000,00
Total	€ 6.104.073,60	€ 3.445.538,40	€ 4.138.965,00	€ 5.434.641,00	€ 4.798.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.430.097,04	€ 2.171.831,76	€ 1.320.477,88		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,23	0,42	0,35	0,26	0,30
Severely injured	0,36	0,63	0,52	0,40	0,45
Slightly injured	0,22	0,38	0,32	0,24	0,28
Total	0,81	1,43	1,19	0,91	1,03
Average	1,07				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure) and thermoplastic (structure). Thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (1,07) indicates that the benefits are higher than the investment costs of the measure. This is the case for all materials except for paint (flatline) and thermoplastic flatline.

- **Motorways: RW 35 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 25 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Motorways: RW 50 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 25 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 761.673,60	€ 429.938,40	€ 516.465,00	€ 678.141,00	€ 598.800,00
25 cm edge line	€ 5.342.400,00	€ 3.015.600,00	€ 3.622.500,00	€ 4.756.500,00	€ 4.200.000,00
Total	€ 6.104.073,60	€ 3.445.538,40	€ 4.138.965,00	€ 5.434.641,00	€ 4.798.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.430.097,04	€ 1.396.177,56	€ 1.047.275,56		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,23	0,42	0,35	0,26	0,30
Severely injured	0,23	0,41	0,34	0,26	0,29
Slightly injured	0,17	0,30	0,25	0,19	0,22
Total	0,63	1,12	0,94	0,71	0,81
Average	0,84				

According to the comparison of the BCR the only cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline). Coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline) markings do not appear to be cost-effective. Regardless of the chosen road marking material, the average benefit-cost ratio (0,84) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 25 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 761.673,60	€ 429.938,40	€ 516.465,00	€ 678.141,00	€ 598.800,00
25 cm edge line	€ 5.342.400,00	€ 3.015.600,00	€ 3.622.500,00	€ 4.756.500,00	€ 4.200.000,00
Total	€ 6.104.073,60	€ 3.445.538,40	€ 4.138.965,00	€ 5.434.641,00	€ 4.798.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 8.580.582,24	€ 4.653.925,20	€ 2.527.121,46		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	1,41	2,49	2,07	1,58	1,79
Severely injured	0,76	1,35	1,12	0,86	0,97
Slightly injured	0,41	0,73	0,61	0,47	0,53
Total	2,58	4,57	3,81	2,90	3,28
Average	3,43				

According to the comparison of the BCR the most cost-effective road marking over a lifetime of 4 years is coldspray plastic (flatline) followed by coldplastic (structure), thermoplastic (structure), thermoplastic (flatline) and paint (flatline). Regardless of the

chosen road marking material, the average benefit-cost ratio (3,43) indicates that the benefits are higher than the investment costs of the measure.

- **Primary roads: RW 50 (mcd*m^{-2}*lx^{-1}) with 12.5 cm for centre lines and 25 cm for edge lines**

  Currently, the social cost-benefit analysis cannot be calculated as there is no crash and injury data available for the target crashes on primary roads in the CARE database.

3.23. Slovenia

3.23.1. Current situation

3.23.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	2240	1120	3360
Primary road	86	43	129
Source: WP1 survey			

3.23.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	15
Primary road	12/15	12/15
Source: WP1 survey		

3.23.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.23.2. Road marking measures to be calculated

The road markings on motorways and primary roads in Slovenia already meet the visibility and width levels recommended by the study or have higher width levels in place. As a result, there is no need to calculate a social cost-benefit analysis.

3.24. Spain

3.24.1. Current situation

3.24.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.24.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15	15
Primary road	15	15
Source: WP1 survey		

3.24.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	No data delivered	No data delivered
Night-time: wet (RW)	No data delivered	No data delivered
Day-time: dry (Qd)	No data delivered	No data delivered
Source: WP1 survey		

3.24.2. Road marking measures to be calculated

There is no data about road marking visibility on ***motorways*** available. The marking widths for edge and centre lines on motorways meet the recommended criteria of 15 cm but the not the recommended criterion of 20 cm for edge lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 150 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 100 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 130 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

There is no data about road marking visibility on ***primary roads*** available. The marking widths for edge and centre lines on primary roads are higher than recommended criteria of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 150 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 100 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

3.24.3. Input values for social cost-benefit analysis

3.24.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.592.359,00	1.720.862,37
Serious injury	254.777,00	275.337,50
Slight injury	6.938,00	7.497,90
The average harmonised inflation of Spain in 2022: 8.07% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.24.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	114	No crash and injury data available
	Seriously injured	442	
	Slightly injured	3915	
Night-time: wet	Fatally injured	10	
	Seriously injured	40	
	Slightly injured	1137	
Day-time: dry	Fatally injured	215	
	Seriously injured	863	
	Slightly injured	7665	

3.24.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.24.4. Social cost-benefit analysis results

Currently, the social cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads. Furthermore, there is no crash and injury data available for the target crashes on primary roads in the CARE database.

3.25. Sweden

3.25.1. Current situation

3.25.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	8488	4244	12732
Primary road	12602	6301	18903
Source: WP1 survey			

3.25.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	15
Primary road	10/15	15
Note: Road markings differ depending on AADT, speed and width of the road.		
Source: WP1 survey		

3.25.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.25.2. Road marking measures to be calculated

Swedish ***motorways*** already meet the visibility criteria for R_L (150), RW (35) and Qd (130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200/300, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. The marking widths for edge and centre lines on motorways meet or are higher than the recommended criteria of 15 cm for centre lines and 15/20 cm for edge lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 30 cm for edge lines

- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 30 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 30 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 30 cm for edge lines

Swedish ***primary roads*** already meet the visibility criteria for R_L (150), RW (35) and Qd (130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. The marking width of centre lines on primary roads meet are higher than the recommended criterion of 12 cm for centre lines. However, for the marking widths it is unclear how many edge lines meet a width of 10 or 15 cm. Therefore, it is assumed that the edge line width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. This value is lower than the recommended width of 12 cm.

Therefore, the social cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines

3.25.3. Input values for social cost-benefit analysis

3.25.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.160.235,00	2.284.664,54
Serious injury	399.728,00	422.752,33
Slight injury	19.561,00	20.687,71
The average harmonised inflation of Sweden in 2022: 5.76%		
Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.25.3.2. Casualties (CARE data 2017-2020): single vehicle crashes without alcohol involvement (4 years)

Condition	Injuries by severity	Motorway	Primary road
Night-time: dry	Fatally injured	1	No crash and injury data available
	Seriously injured	14	
	Slightly injured	94	
Night-time: wet	Fatally injured	1	
	Seriously injured	13	
	Slightly injured	58	
Day-time: dry	Fatally injured	2	
	Seriously injured	18	
	Slightly injured	122	

3.25.3.3. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
30 cm	€ 1.418,40	€ 973,50	€ 1.710,00

3.25.4. Social cost-benefit analysis results

- **Motorways: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 3.009.844,80	€ 2.065.767,00	€ 3.628.620,00
30 cm edge line	€ 12.039.379,20	€ 8.263.068,00	€ 14.514.480,00
Total	€ 15.049.224,00	€ 10.328.835,00	€ 18.143.100,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.284.664,54	€ 5.918.532,62	€ 1.944.644,74
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	0,15	0,22	0,13
Severely injured	0,39	0,57	0,33
Slightly injured	0,13	0,19	0,11
Total	0,67	0,98	0,56
Average		0,74	

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. Regardless of the chosen road marking material, the average benefit-cost ratio (0,74) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: R_L 300 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 6.478.041,60	€ 3.656.630,40	€ 4.392.540,00	€ 5.767.596,00	€ 5.092.800,00
30 cm edge line	€ 25.912.166,40	€ 14.626.521,60	€ 17.570.160,00	€ 23.070.384,00	€ 20.371.200,00
Total	€ 32.390.208,00	€ 18.283.152,00	€ 21.962.700,00	€ 28.837.980,00	€ 25.464.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.284.664,54	€ 5.918.532,62	€ 1.944.644,74		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,07	0,12	0,10	0,08	0,09
Severely injured	0,18	0,32	0,27	0,21	0,23
Slightly injured	0,06	0,11	0,09	0,07	0,08
Total	0,31	0,56	0,46	0,35	0,40
Average	0,42				

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. Regardless of the chosen road marking material, the average benefit-cost ratio (0,42) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: RW 50 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 6.478.041,60	€ 3.656.630,40	€ 4.392.540,00	€ 5.767.596,00	€ 5.092.800,00
30 cm edge line	€ 25.912.166,40	€ 14.626.521,60	€ 17.570.160,00	€ 23.070.384,00	€ 20.371.200,00
Total	€ 32.390.208,00	€ 18.283.152,00	€ 21.962.700,00	€ 28.837.980,00	€ 25.464.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.284.664,54	€ 5.495.780,29	€ 1.199.887,18		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,07	0,12	0,10	0,08	0,09
Severely injured	0,17	0,30	0,25	0,19	0,22
Slightly injured	0,04	0,07	0,05	0,04	0,05
Total	0,28	0,49	0,41	0,31	0,35
Average	0,37				

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. Regardless of the chosen road marking material, the average benefit-cost ratio (0,37) indicates that the benefits are lower than the investment costs of the measure.

- **Motorways: Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 6.478.041,60	€ 3.656.630,40	€ 4.392.540,00	€ 5.767.596,00	€ 5.092.800,00
30 cm edge line	€ 25.912.166,40	€ 14.626.521,60	€ 17.570.160,00	€ 23.070.384,00	€ 20.371.200,00
Total	€ 32.390.208,00	€ 18.283.152,00	€ 21.962.700,00	€ 28.837.980,00	€ 25.464.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 4.569.329,08	€ 7.609.541,94	€ 2.523.900,62		
Benefit-cost ratio	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	0,14	0,25	0,21	0,16	0,18
Severely injured	0,23	0,42	0,35	0,26	0,30
Slightly injured	0,08	0,14	0,11	0,09	0,10
Total	0,45	0,80	0,67	0,51	0,58
Average	0,60				

For all road markings the BCR is lower than 1 indicating that the measure is not cost-effective over a lifetime of 4 years. Regardless of the chosen road marking material, the average benefit-cost ratio (0,60) indicates that the benefits are lower than the investment costs of the measure.

- **Primary roads**

Currently, the social cost-benefit analysis cannot be calculated as there is no crash and injury data available for the target crashes on primary roads in the CARE database.

4. CONCLUSIONS

4.1. General findings

The general findings that are presented here are based on the benefit-cost ratio for six Member States that currently apply lower threshold values than the common minimal values for road marking width and visibility evaluated in this study. The other 18 Member States currently have higher visibility levels (but lower width levels) or higher width levels (but lower visibility levels) than the common minimal values in place. This makes it quite complicated to assign the identified effect to reaching the common minimal values for visibility or marking width only as this identified effect can also originate from combining:

- Higher visibility levels (than the common minimum values) with a common minimum level for width
- Higher road marking widths (than the common minimum values) with a common minimum level for visibility

4.1.1. Motorways

- R_L 150, RW 35, Qd 100/130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15/20 cm for edge lines

  These measures could not be calculated as the supplier did not provide unit costs and service life information for these common visibility and width levels.

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

  Only 1 Member State, Hungary, did not yet meet this common minimal value. The benefit-cost ratio amounted to 12.26. This ratio is higher than 1 indicating that the benefits are higher than the investment costs of the measure. In theory, this means that the measure is cost-effective and generates benefits. However, as this positive BCR was only achieved for 1 Member State this result should be handled carefully and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

  Four Member States did not yet meet this common minimal value. These Member States and the related benefit-cost ratio are listed below:

  - Finland: 1.74
  - Germany: 8.12
  - Hungary: 9.55
  - Netherlands: 11.02

  The benefit-cost ratio ranges from 1.74 in Finland to 11.02 in The Netherlands. In all four Member States the ratio is higher than 1 indicating that the benefits are higher than the investment costs of the measure. This would mean that the measure is cost-effective and generates benefits. However, as this positive BCR was only achieved for four Member States this result should be considered carefully and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

Only 1 Member State, Hungary, did not yet meet this common minimal value. The benefit-cost ratio amounted to 6.91. This ratio is higher than 1 indicating that the benefits are higher than the investment costs of the measure. In theory, this means that the measure is cost-effective and generates benefits. However, as this positive BCR was only achieved for 1 Member State we should be careful with this result and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

  Six Member States did not yet meet this common minimal value. These Member States and the related benefit-cost ratio are listed below:

  - Austria 1.08
  - Finland 0.98
  - Germany 4.57
  - Hungary 5.38
  - Netherlands 6.21
  - Portugal: 2.10

  The benefit-cost ratio ranges from 0.98 in Finland to 6.21 in The Netherlands. In all six Member States the ratio is higher than 1 indicating that the benefits are higher than the investment costs of the measure. In theory, this means that the measure is cost-effective and generates benefits. However, as this positive BCR was only achieved for six Member States we should be careful with this result and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

  Five Member States did not yet meet this common minimal value. These Member States and the related benefit-cost ratio are listed below:

  - Austria 0.20
  - Finland 0.84
  - Germany 0.08
  - Netherlands 2.21
  - Portugal: 0.77

  The benefit-cost ratio ranges from 0.20 in Austria to 2.21 in The Netherlands. In five of the six Member States the ratio is lower than 1 indicating that the costs are higher than the benefits of the measure. In theory, this means that the measure is not cost-effective and creates no benefits. Only in the Netherlands, the measure seems to be cost-effective and t generate benefits. Therefore, we should be careful with this result and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

  Only 1 Member State, Hungary, did not yet meet this common minimal value. The benefit-cost ratio amounted to 16.04. This ratio is higher than 1 indicating that the benefits are higher than the investment costs of the measure. In theory, this means that the measure is cost-effective and generates benefits. However, as this positive BCR was only achieved for 1 Member State we should be careful with this result and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

  Six Member States did not yet meet this common minimal value. These Member States and the related benefit-cost ratio are listed below:

  - Austria 1.23
  - Finland 1.90
  - Germany 8.57
  - Hungary 12.49
  - Netherlands 14.84
  - Portugal: 4.74

  The benefit-cost ratio ranges from 1.23 in Austria to 14.84 in The Netherlands. In all six Member States the ratio is higher than 1 indicating that the benefits are higher than the investment costs of the measure. In theory, this means that the measure is cost-effective and generates benefits. However, as this positive BCR was only achieved for six Member States we should be careful with this result and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

4.1.2. Primary roads

The effect of common minimal values for road markings on primary roads could only be calculated Finland. The benefit-cost ratios are indicated below:

- R_L 200 mcd*m^{-2}*lx^{-1} with 12 cm for centre and edge lines: 3.11
- RW 50 mcd*m^{-2}*lx^{-1} with 12 cm for centre and edge lines: 0.31
- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre and edge lines: 2.07

The benefit-cost ratio for R_L 200 and Qd 160 is higher than 1 indicating that the benefits are higher than the investment costs of the measure. However, as the BCR could only be calculated for 1 Member State we should be careful with this result and further research is needed to reliably determine if this measure generates road safety benefits and is cost-effective.

For the other Member States, it was not possible to calculate the effect of common minimal values for road markings for primary since there is no crash and injury data available for single-vehicle crashes on primary roads in the CARE database. This makes it impossible to calculate the benefit side.

It is important to mention that the common minimal width values for road markings on primary roads are set to 12 cm for centre and edge lines. Almost all of the 24 Member States participating in this study apply higher width values (for edge lines, centre lines or both) than commonly defined on primary roads with sometimes lower visibility values than commonly defined. As mentioned in the introduction of this section, the combination of a common minimal visibility level and higher width than commonly defined makes it quite complicated to conclude which characteristic (the higher width or common minimal visibility level) generates the road safety benefit. Therefore, these results are omitted from this conclusion as they are out of scope for this study.

4.2. How to use these results?

These results must be interpreted with caution as they are based on the benefit cost ratio of only six Member States and the applied method suffers from several severe limitations listed in paragraph 2.6. The most important limitation is that the found effects of the common minimum visibility and width levels for road markings are significantly overestimated. Firstly, all single-vehicle crashes without alcohol involvement are defined as the target crashes impacted by these measures. In other words, a 100% effectiveness on target crashes is assumed, i.e., the improved marking reduces the target crashes to zero. This effectiveness on target crashes can only be adjusted with the use of CMFs. CMFs could assist in lowering the overestimation, but there are no reliable CMFs available for the Europe. Furthermore, it is widely acknowledged that crashes are the results of interaction between multiple factors (road users, environment/road, vehicle). In this report, the focus only lies on determining the role that the visibility and/or width of road markings plays in crash occurrence/avoidance. It is extremely complicated to succeed in determining whether the visibility of the road markings played a role in the occurrence of an accident especially since this type of information is not available in the crash data base. Because of all these reasons, it is currently not possible to solve this overestimation and the assumed effectiveness on the target crashes is very likely not equal to 100% but to a lower percentage.

Secondly, the effect of incremental higher visibility and width levels cannot be considered. This is only possible with crash modification factors (CMFs). For this study, it means that the incremental change in visibility and width levels was only considered in the cost side but not in the benefit side without using CMFs. To illustrate, in order to include this incremental change in the benefit side we should know or find a value indicating how many crashes are caused in Europe by bad marking visibility or a too narrow marking width (which is not available). For example, we should know how many crashes can be avoided if we go from a visibility of 100 to 130 to 150 $mcd*m^{-2}*lx^{-1}$ and this incremental change can only be measured by means of CMFs if they are available. For the same reason, the analysis cannot differentiate between the costs and benefits of improved road markings for human drivers or ADAS. This is only possible with the use of CMFs.

Thirdly, for some Member States there is no or very limited crash and injury data available for the target crashes in the CARE database. These low numbers do not imply that no crashes or injuries occurred on these roads in certain Member States but are very likely the result of the accuracy of the crash registration process (missing road category, missing crash circumstances, etc.).

Finally, there are large differences in official estimates of road crash costs in European countries. The cost per fatality ranges from €0.7 million to €3.2 million. The costs per serious injury range from €30.000 to €1 million, and the costs per slight injury from €316 to €75.000. The differences are largely explained by differences in methodologies, in particular whether or not a willingness to pay method is applied to estimate human costs, differences in costs components that are included, different definitions of serious and slight injuries and differences in reporting rates of crashes and injuries (Wijnen et al., 2017).

Limited crash data and higher unit costs per casualty severely impact the benefit-cost ratio result. Member States with limited crash data and higher unit costs per casualty have a lower BCR as they need a longer time to (need to save more casualties than reported) to recover the investment. Whereas Member States with more crash data and more average unit costs per casualty will need to undertake less efforts in order to recover the investment costs and have a higher chance to reach a positive BCR within the service life time.

To conclude, the findings cannot be extrapolated to all Member States given these differences between Member States. Given the limited availability of certain data and the assumption that all target crashes are affected by the measures, leading to a significant overestimation of the benefits, it is strongly advised to treat these results with caution and to bear in mind the possible bias in these results. Therefore, the results of this analysis only serve as a first indication of the expected costs and benefits of the minimum common visibility and width levels for road markings on motorways and primary roads in Europe. Put differently, for some minimum levels, the results indicate the direction of the effect but the value of the effect is highly disputable.

It is strongly advised to research these effects further when CMFs become available that reflect the incremental change in visibility and width levels. This is the only approach to capture the effect of incremental higher road marking visibility and width levels.

For some common specifications, the results indicate a positive direction related to this introduction however the value of the effect is highly disputable. However, it is expected that introducing common specifications for road markings and signs will be inevitable in the future when autonomous vehicles will become more common.

REFERENCES

- Ben-Bassat, T. (2019). Are ergonomically designed road signs more easily learned? *Applied Ergonomics*, *78*, 137–147. https://doi.org/10.1016/j.apergo.2019.02.009
- Ben-Bassat, T., & Shinar, D. (2006). Ergonomic guidelines for traffic sign design increase sign comprehension. *Human Factors*, *48*(1), 182–195. https://doi.org/10.1518/001872006776412298
- Carlson, P. J., Park, E. S., & Andersen, C. K. (2009). Benefits of Pavement Markings: A Renewed Perspective Based on Recent and Ongoing Research. *Transportation Research Record*, *2107*(1), 59–68. https://doi.org/10.3141/2107-06
- Carlson, P. J., Park, E. S., & Kang, D. H. (2013a). Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety. *Transportation Research Record*, *2337*(1), 59–66. https://doi.org/10.3141/2337-08
- Carlson, P. J., Park, E. S., & Kang, D. H. (2013b). Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety. *Transportation Research Record*, *2337*(1), 59–66. https://doi.org/10.3141/2337-08
- Chang, K., Ramirez, M. V., Dyre, B., Mohamed, M., & Abdel-Rahim, A. (2019). Effects of longitudinal pavement edgeline condition on driver lane deviation. *Accident Analysis and Prevention*, *128*, 87–93. https://doi.org/10.1016/j.aap.2019.03.011
- Cicchino, J. B. (2018). Effects of lane departure warning on police-reported crash rates. *Journal of Safety Research*, *66*, 61–70. https://doi.org/10.1016/j.jsr.2018.05.006
- Eurostat. (2022). *HICP - annual data (average index and rate of change)*. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=prc_hicp_aind
- Hickman, J. S., Guo, F., Camden, M. C., Hanowski, R. J., Medina, A., & Mabry, J. E. (2015). Efficacy of roll stability control and lane departure warning systems using carrier-collected data. *Journal of Safety Research*, *52*, 59–63. https://doi.org/10.1016/j.jsr.2014.12.004
- Inflation.eu. (2022). *Harmonised inflation Belgium 2022 – HICP inflation Belgium 2022*. https://www.inflation.eu/en/inflation-rates/belgium/historic-inflation/hicp-inflation-belgium-2022.aspx
- Ng, A. W. Y., & Chan, A. H. S. (2007). The guessability of traffic signs: Effects of prospective-user factors and sign design features. *Accident Analysis & Prevention*, *39*(6), 1245–1257. https://doi.org/10.1016/j.aap.2007.03.018
- Park, E. S., Carlson, P. J., Porter, R. J., & Andersen, C. K. (2012). Safety effects of wider edge lines on rural, two-lane highways. *Accident Analysis & Prevention*, *48*, 317–325. https://doi.org/10.1016/j.aap.2012.01.028
- Penmetsa, P., Hudnall, M., & Nambisan, S. (2019). Potential safety benefits of lane departure prevention technology. *IATSS Research*, *43*(1), 21–26. https://doi.org/10.1016/j.iatssr.2018.08.002
- Shinar, D., Dewar, R., Summala, H., & Zakowska, L. (2003). Traffic sign symbol comprehension: A cross-cultural study. *Ergonomics*, *46*(15), 1549–1565. https://doi.org/10.1080/0014013032000121615
- Spicer, R., Vahabaghaie, A., Bahouth, G., Drees, L., Martinez von Bülow, R., & Baur, P. (2018). Field effectiveness evaluation of advanced driver assistance systems. *Traffic Injury Prevention*, *19*(sup2), S91–S95. https://doi.org/10.1080/15389588.2018.1527030
- Sternlund, S. (2017). The safety potential of lane departure warning systems—A descriptive real-world study of fatal lane departure passenger car crashes in Sweden. *Traffic Injury Prevention*, *18*, S18–S23. https://doi.org/10.1080/15389588.2017.1313413

- Wijnen, W., Weijermans, W., Vanden Berghe, W., Schoeters, A., Bauer, R., Carnis, L., Elvik, R., Theofilatos, A., Filtness, A., Reed, S., Perez, C., & Martsensen, H. (2017). *Crash cost estimates for European countries* [Deliverable 3.2 of the H2020 project SafetyCube.].
- Yuan, L., Ma, Y.-F., Lei, Z.-Y., & Xu, P. (2014). Driver's Comprehension and Improvement of Warning Signs. *Advances in Mechanical Engineering*, *6*(0), Article 0. https://cyberleninka.org/article/n/1405040

ANNEX

ANNEX 1.1: OVERVIEW OF COSTS TO IMPLEMENT ROAD MARKINGS OF CERTAIN VISIBILITY LEVELS AND WIDTH

Initial performance requirements for Type II markings: RW 50 / RL 300 / Qd 160

Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
Type of Lane	**Flatline**	**Flatline**	**Structure**	**Flatline**	**Structure**
Film thickness in mm	0,6	0,4	-	3,0	-
Density	1,57	1,58	1,84	2,00	2,00
Consumption kg / m²	0,9	0,6	2,6	6,0	4,0
Price € / kg	2,00	3,50	2,50	1,40	1,40
Drop-On Bead consumption kg / m²	0,6	0,6	0,5	0,6	0,5
Price € / kg Bead	1,10	1,10	0,80	1,10	0,80
Total Material Costs / m²	**2,54 €**	**2,87 €**	**6,90 €**	**9,06 €**	**6,00 €**
Cost per km lane width					
10 cm	254 €	287 €	690 €	906 €	600 €
12 cm	305 €	345 €	828 €	1.087 €	720 €
12,5 cm	318 €	359 €	863 €	1.133 €	750 €
15 cm	382 €	431 €	1.035 €	1.359 €	900 €
18 cm	458 €	517 €	1.242 €	1.631 €	1.080 €
20 cm	509 €	574 €	1.380 €	1.812 €	1.200 €
22,5 cm	572 €	646 €	1.553 €	2.039 €	1.350 €
24 cm	611 €	689 €	1.656 €	2.174 €	1.440 €
25 cm	636 €	718 €	1.725 €	2.265 €	1.500 €
30 cm	763 €	862 €	2.070 €	2.718 €	1.800 €
Min Lifetime in years	0,5	1,0	2,0	2,0	2,0
Expectable Lifetime in years	1,0	2,0	4,0	4,0	3,0

Service life for 4 years (calculation based on expectable life time in years and converted to the costs per km lane width over a period of 4 years):

Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
Type	**Flatline**	**Flatline**	**Structure**	**Flatline**	**Structure**
10 cm	1018 €	574 €	690 €	906 €	800 €
12 cm	1221 €	689 €	828 €	1087 €	960 €
12,5 cm	1272 €	718 €	863 €	1133 €	1000 €
15 cm	1526 €	862 €	1035 €	1359 €	1200 €
18 cm	1832 €	1034 €	1242 €	1631 €	1440 €
20 cm	2035 €	1149 €	1380 €	1812 €	1600 €
22,5 cm	2290 €	1292 €	1553 €	2039 €	1800 €
24 cm	2442	1379 €	1656 €	2174 €	1920 €
25 cm	2544 €	1436 €	1725 €	2265 €	2000 €
30 cm	3053 €	1723 €	2070 €	2718 €	2400 €

Initial performance requirements for Type I (low standard) markings: RL200 / Qd160

Material	Paint	Coldspray Plastic	Thermoplastic
Type of Lane	Flatline	Flatline	Flatline
Film thickness in mm	0,3	0,25	3
Density of Material	1,57	1,58	2,00
Consumption kg / m²	0,47	0,40	6,00
Price € / kg	2,00	3,50	0,90
Drop-On Bead consumption kg / m²	0,4	0,4	0,5
Price € / kg Bead	0,60	0,60	0,60
Total Material Costs / m²	**1,18 €**	**1,62 €**	**5,70 €**
Cost per km lane width			
10 cm	118 €	162 €	570 €
12 cm	142 €	195 €	684 €
12,5 cm	148 €	203 €	713 €
15 cm	177 €	243 €	855 €
18 cm	213 €	292 €	1.026 €
20 cm	236 €	325 €	1.140 €
22,5 cm	266 €	365 €	1.283 €
24 cm	284 €	389 €	1.368 €
25 cm	296 €	406 €	1.425 €
30 cm	355 €	487 €	1.710 €
Min Lifetime in years	0,5	1,0	2,0
Expectable Lifetime in years	1,0	2,0	4,0

Service life for 4 years (calculation based on expectable life time in years and converted to the costs per km lane width over a period of 4 years):

Material	Paint	Coldspray Plastic	Thermoplastic
Type	**Flatline**	**Flatline**	**Flatline**
10 cm	473 €	325 €	570 €
12 cm	567 €	389 €	684 €
12,5 cm	591 €	406 €	713 €
15 cm	709 €	487 €	855 €
18 cm	851 €	584 €	1.026 €
20 cm	946 €	649 €	1.140 €
22,5 cm	1.064 €	730 €	1.283 €
24 cm	1.135 €	779 €	1.368 €
25 cm	1.182 €	811 €	1.425 €
30 cm	1.418 €	974 €	1.710 €

ANNEX 1.2: LENGTH IN KM OF EDGE LINES AND CENTRE LINES ON MOTORWAYS AND PRIMARY ROADS IN EACH MEMBER STATE

Country	Motorways		Primary roads		Remark
	Centre line	Edge line	Centre line	Edge line	
Austria	5.145	9.000	-	-	No definition of primary roads
Belgium	400	1.700	-	-	Only for Wallonia (Total km motorway = 1763 Km primary road = 13229)
Bulgaria	1600	3200	3000	6000	
Croatia	4.319	8.619	7.175	10.763	The data for the motorways is for one direction.
Cyprus	-	-	-		
Estonia	-	-	-		No roads classified as motorways
Finland	1.900	3.700	13.000	26.000	
France	42.200	46.600	13.500	26.500	
Germany	21.667	43.333	36.667	73.333	
Hungary	881	5.036	2.612	15.674	
Iceland	-	-	4.490	6.620	No roads classified as motorways
Ireland	250	1.888	4.000	4.298	
Italy	-	-	-		No data delivered
Latvia	-	-	-		No roads classified as motorways
Lithuania	860	1.720	1.446	2.892	
Luxembourg	330	1.000	-	-	No data delivered
Norway	500	4.000	4.000	8.000	
Poland					No data delivered
Portugal	7.110	11.940	-	-	
Romania	634	3.840	10.644	35.480	
Slovakia	499	2.100	268	1.082	
Slovenia	1.120	2.240	43	86	
Spain	-	-	-	-	No data delivered
Sweden	4.244	8.488	6.301	12.602	
The Netherlands					longitudinal markings on both types of roads is totalized: 26.796km (km motorway = 2756; Km primary road = 2629)

ANNEX 1.3: CURRENT SITUATION REGARDING ROAD MARKING WIDTH AND VISIBILITY LEVELS ON MOTORWAYS AND PRIMARY ROADS OF EACH MEMBER STATE

Standard widths of longitudinal road markings

	Motorways		Primary roads	
Country	Centre line	Edge line	Centre line	Edge line
Austria	15	20/30[1]	NA	NA
Belgium (Wallonia)	20	30	15	20
Bulgaria	15	25	10	15
Croatia	20	20	12/15	12/15
Cyprus	20	20	10/15	10/15
Estonia	15[2]	20/30[2]	10/15	10/15/20/30
Finland*	10	20	10	10
France**	15	22.5	12/15	18/22.5
Germany***	15	15/30	12	12/25
Hungary	12/15	15/20	12	15
Iceland****	NA	NA	10	10
Ireland	10	15	15	15
Italy	15	25	15[3]	12/25[3]
Latvia	NA	NA	10/15/20	10/15/20
Lithuania	15	30	12	25
Luxembourg	15	22.5	12	12
Norway	15	30	10/15	10/15
Poland	12/24	24	12/24	24
Portugal	15	20	12	15
Romania	15	25	15	15
Slovakia	12.5	25	12.5	25
Slovenia	15	20	12/15	12/15
Spain	15	15	15	15
Sweden*****	15	30	15	10/15
The Netherlands	15	20	15	15/20

NA – Not applicable
1 - 30 cm edge line at exit and entries; 2 – Expressways (2+2 and 2+1 lane roads); 3 – On the suburban and main urban and suburban motorways the module is: 25-15-25, on the suburban secondary and urban traffic and neighborhood the module is: 15-12-15, while on local roads (urban and extra-urban) the form is: 12-10-12.
* Centre line can be 30 cm or 40 cm (or 60 cm) on motorway weaving sections. Edge line can be 30 cm or 40 cm on primary road or motorway weaving sections (and even 60 cm) on motorway weaving sections.
** "Non motorway dual carriageways" - centre line: 15cm, edge line: 22,5 cm;
** "Single carriageways" - centre line: 12 cm, edge line: 18 cm
*** Motorways: left edge line 15 or 30 cm, right edge line or dashed right edge line 30 cm, dashed centre line 15 cm. National Roads: edge lines 12 cm, edge lines to separate hard shoulder/bus stops or dashed right edge line 25 cm, dashed centre marking: 12 cm.
**** On the busiest road outside Reykjavík 20 cm edge and 12 cm centre lines are used.
***** Depending on AADT, speed and width of the road, the road markings differ.

Minimal values of daytime and night-time visibility (for condition of wetness and rain), luminance factor and skid resistance for road markings on motorways

	Motorways									
Country	**Qd – NM**	**Qd - RE**	**R_L – NM**	**R_L - RE**	**RW – NM**	**RW - RE**	**RR – NM**	**RR - RE**	**β**	**SRT**
Austria	100/130[1]	100/130[1]	200	100	35	25	35	25	NR	45
Belgium	160/130[1]	160/130[1]	150	150	25	25	25	25	NR	45
Bulgaria	160	130	300	150	50	35	NR	NR	0.5	55
Croatia	160	100	300	150	50	35	NR	NR	0.4	45
Cyprus	130/100[2]	NR	200/150[2]	NR	35	NR	NR	NR	LF6	45
Estonia*	130	NR	150	NR	35	NR	35	NR	NR	55
Finland	130	130	150	100	NR	NR	NR	NR	0.8	45
France	100/130	NR	150	NR	35	NR	35	NR	NR	45
Germany	160	105[3]	300[4]/200	80[3]	75[4]/50	20[3]	NR	NR	NR	45
Hungary	130	130	200	200	75	75	200	200	0.6	45
Iceland	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ireland	200	100	200	100	50	35	NA	NA	0.4/0.3	50
Italy	130	100	150	110	50	35	35	25	0.7	45
Latvia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lithuania	130	130	200	200	50	50	NR	NR	NR	45
Luxembourg	160	130	300	150	75	35	NR	NR	NR	55
Norway	130/100[2]	NR	150/100[2]	NR	50	NR	NR	NR	NR	50
Poland	130/160[1]	100/130[1]	250	200	50	35	NR	NR	0.40/0.50[1]	0.45[5]
Portugal	NR	100	200	100	NR	NR	NR	NR	0.3	45
Romania	160	160	300	300	75	75	NR	NR	0.6	45
Slovakia	160	100	300	100	35/50[6]	35/50[6]	35/50[6]	35/50[6]	0.3	45
Slovenia	160	130	300	100	50	35	NR	NR	0.4	45
Spain	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	130	NR	150	NR	35	NR	NR	NR	NR	50
The Netherlands	130	<130	100	<100	35	<35	NR	NR	0.4/0.6	55

NM – new markings; RE – minimal value for renewal; NR – not requested; NA – not applicable; ND – no data
* Expressways (2+2 and 2+1 lane roads)
1 - first values for asphalt, second for concrete; 2 – first value for white, second for yellow markings; 3 - recommended values according to ZTV M 13 for the renewal of used road markings. ZTV M 13 also defines (higher) values for the end of the warranty period. 4 - first value only for tapes; 5 - PFT units; 6 – second value for plastic road markings

Minimal values of daytime and night-time visibility (for condition of wetness and rain), luminance factor and skid resistance for road markings on primary roads

	Primary roads									
Country	**Qd – NM**	**Qd - RE**	**R_L – NM**	**R_L - RE**	**RW – NM**	**RW - RE**	**RR – NM**	**RR - RE**	**β**	**SRT**
Austria	NA	NA	NA	NA	NA	NA	NA	NA	NR	
Belgium	160/130[1]	160/130[1]	150	150	NR	NR	NR	NR	NR	45
Bulgaria	160	130	300	150	50	35	NR	NR	0.5	55
Croatia	130	100	200	100	50[2]	35[2]	NR	NR	0.4	45
Cyprus	130/100[3]	NR	200/150[3]	NR	35	NR	NR	NR	LF6	45
Estonia	130	NR	150	100	35	NR	35	NR	NR	55
Finland	130	130	150	100	NR	NR	NR	NR	0.8	45
France	100/130	NR	150	NR	35	NR	35	NR	NR	45
Germany	160	105[4]	300[5]/200	80[4]	75[5]/50	20[4]	NR	NR	NR	45
Hungary	130	130	150	150	50	50	150	150	0.6	45
Iceland	130	NR	150	100	NR	NR	NR	NR	NR	0.52[6]
Ireland	200	100	200	100	50	35	NA	NA	0.4/0.3	50
Italy	NR	100	NR	150	NR	35	NR	25	0.87	45
Latvia	100	100	150	150	50	50	NR	NR	5	45
Lithuania	130	130	200	200	50	50	NR	NR	NR	45
Luxembourg	160	130	200	100	50	25	NR	NR	NR	45
Norway	130/100[3]	NR	150/100[3]	NR	50	NR	NR	NR	NR	50
Poland	130/160[1]	100/130[1]	250	200	50	35	NR	NR	0.40/0.50[1]	0.45[6]
Portugal	160	100	200	100	50	35	50	35	0.6	45
Romania	160	160	300	300	75	75	NR	NR	0.6	45
Slovakia	160	100	300	100	35/50[7]	35/50[7]	35/50[7]	35/50[7]	0.3	45
Slovenia	160	130	300	100	50	35	NR	NR	0.4	45
Spain	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	130	NR	150	NR	35	35	NR	NR	NR	0.5[6]
The Netherlands	130	<130	100	<100	35	<35	NR	NR	0.4/0.6	55

NM – new markings; RE – minimal value for renewal; NR – not requested; NA – not applicable; ND – no data
1 - first values for asphalt, second for concrete; 2 – only for Type II markings; 3 – first value for white, second for yellow markings; 4 - recommended values according to ZTV M 13 for the renewal of used road markings. ZTV M 13 also defines (higher) values for the end of the warranty period; 5 – first value only for tapes; 6 – PFT units; 7 - second value for plastic road markings

ANNEX 1.4: HISTORICAL AND CURRENT UNIT COSTS OF A FATAL, SERIOUS AND SLIGHT INJURED PERSON IN EACH MEMBER STATE

Unit costs of a fatal, serious and slight injured person in each Member State in 2015 (Wijnen et al., 2017)*.*

	Costs per casualty (2015) in Euro		
Country	**Fatality**	**Serious injury**	**Slight injury**
Austria	3.014.655,00	381.285,00	26.880,00
Belgium	2.021.091,00	307.364,00	19.766,00
Bulgaria	1.355.315,00	220.390,00	57.267,00
Croatia	2.230.967,00	290.042,00	22.259,00
Cyprus	1.027.088,00	135.535,00	9.921,00
Estonia	2.819.426,00	959.011,00	36.802,00
Finland	2.340.452,00	671.383,00	29.111,00
France	2.944.662,00	368.029,00	14.070,00
Germany	1.177.194,00	119.480,00	4.954,00
Hungary	2.147.976,00	501.194,00	553,00
Iceland	2.861.281,00	364.914,00	71.742,00
Ireland	1.965.163,00	225.511,00	20.860,00
Italy	1.615.566,00	211.860,00	18.245,00
Latvia	1.141.935,00	28.205,00	296,00
Lithuania	988.981,00	89.804,00	NA
Luxembourg	NA	NA	NA
Norway	2.690.394,00	845.812,00	52.970,00
Poland	814.504,00	975.074,00	11.536,00
Portugal	838.109,00	136.365,00	35.391,00
Romania	NA	NA	NA
Slovakia	652.238,00	141.504,00	20.767,00
Slovenia	2.118.429,00	247.550,00	24.412,00
Spain	1.592.359,00	254.777,00	6.938,00
Sweden	2.160.235,00	399.728,00	19.561,00
The Netherlands	2.504.928,00	269.149,00	6.031,00

Inflation level in Member States 2015 compared to 2022 (Eurostat, 2022; Inflation.eu, 2022).

Country	Inflation 2015	Inflation 2022	Difference	Note
Austria	100	106,28	6,28	
Belgium	100	109,32	9,32	
Bulgaria	100	106,78	6,78	EU average no MS specific figure available
Croatia	100	106,78	6,78	EU average no MS specific figure available
Cyprus	100	106,78	6,78	EU average no MS specific figure available
Estonia	100	106,78	6,78	EU average no MS specific figure available
Finland	100	105,45	5,45	
France	100	104,75	4,75	
Germany	100	106,69	6,69	
Hungary	100	109,07	9,07	
Iceland	100	104,69	4,69	
Ireland	100	109,60	9,60	
Italy	100	106,33	6,33	
Latvia	100	106,78	6,78	EU average no MS specific figure available
Lithuania	100	106,78	6,78	EU average no MS specific figure available
Luxembourg	100	107,69	7,69	
Norway	100	106,78	6,78	EU average no MS specific figure available
Poland	100	110,23	10,23	
Portugal	100	105,75	5,75	
Romania	100	106,78	6,78	EU average no MS specific figure available
Slovakia	100	109,63	9,63	
Slovenia	100	107,01	7,01	
Spain	100	108,07	8,07	
Sweden	100	105,76	5,76	
The Netherlands	100	109,58	9,58	

Unit costs of a fatal, serious and slight injured person in each Member State in 2022

	Costs per casualty (2022) in Euro		
Country	**Fatality**	**Serious injury**	**Slight injury**
Austria	3.203.975,33	405.229,70	28.568,06
Belgium	2.209.456,68	336.010,32	21.608,19
Bulgaria	1.447.205,36	235.332,44	61.149,70
Croatia	2.382.226,56	309.706,85	23.768,16
Cyprus	1.096.724,57	144.724,27	10.593,64
Estonia	3.010.583,08	1.024.031,95	39.297,18
Finland	2.468.006,63	707.973,37	30.697,55
France	3.084.533,45	385.510,38	14.738,33
Germany	1.255.948,28	127.473,21	5.285,42
Hungary	2.342.797,42	546.652,30	603,16
Iceland	2.995.475,08	382.028,47	75.106,70
Ireland	2.153.818,65	247.160,06	22.862,56
Italy	1.717.831,33	225.270,74	19.399,91
Latvia	1.219.358,19	30.117,30	316,07
Lithuania	1.056.033,91	95.892,71	NA
Luxembourg	NA	NA	NA
Norway	2.872.802,71	903.158,05	56.561,37
Poland	897.827,76	1.074.824,07	12.716,13
Portugal	886.300,27	144.205,99	37.425,98
Romania	NA	NA	NA
Slovakia	715.048,52	155.130,84	22.766,86
Slovenia	2.266.930,87	264.903,26	26.123,28
Spain	1.720.862,37	275.337,50	7.497,90
Sweden	2.284.664,54	422.752,33	20.687,71
The Netherlands	2.744.900,10	294.933,47	6.608,77

Break-even cost-benefit analysis of a common approach as regards road markings' visibility and width

Final report of the WP5

February, 2023

Directorate-General for Mobility and Transport
Study on road signs and road markings

SUMMARY

As part of the traffic control plan, road markings and road signs provide road users with information regarding the current and upcoming road situation.

The revised Road Infrastructure Safety Management Directive[1] has included new provisions on lane markings and road signs. Member States in particular has been requested to pay specific attention, in their existing and future procedures for road markings and road signs, to readability and detectability for human drivers and automated driver assistance systems.

The Commission has been tasked to set up a group of experts to assess the opportunity to establish common specifications including different elements aiming at ensuring the operational use of road markings and road signs in order to foster the effective readability and detectability of road markings and road signs for human drivers and automated driver assistance systems.

The expert Group on Road Infrastructure Safety – hereafter referred to as "EGRIS" was created in December 2019 and was tasked to assist it in relation to the implementation of the required provisions of the Directive. One of the tasks of EGRIS is, with the help of the sub-group Road Markings and Road Signs, to advise and support the Commission on how to improve the readability and detectability of road markings and road signs, both for human drivers and ADAS systems. The overall aim of this study is to provide the Commission with an up-to-date information to support the work of the MS' experts for the implementation of Article 6(c) of the Directive.

From the overall discussions of the expert group, it was decided to focus on road markings.

In order to establish whether a common approach, in the form of common technical specifications or guidelines for road markings in terms of visibility and width generates road safety benefits, the EGRIS group decided to base its further assessment on two analyses: 1) a social cost-benefit; and 2) a break-even cost-benefit. In this part of the report a break-even cost-benefit analyses for each member state is presented.

A break-even cost-benefit analysis estimates the additional costs of the intervention and calculates how effective the intervention would need to be in reducing the number of crashes or injuries in order for the saved societal crash cost to weigh up against the intervention costs. This economic appraisal approach provides an idea of how 'effective' the measure should be to be 'worth' investing in. This report summarises the methodology, assumptions, limitations and findings of this break-even cost-benefit analysis.

The results of this analysis serve as a first indication of the expected costs and benefits regarding visibility and width levels for road markings on motorways and primary roads in Europe. The findings refer to some Member States for which the data was made available. These preliminary results indicate that introducing common specifications for road markings can result in road safety benefits. For some common specifications, the results indicate a positive direction related to this introduction however the value of the effect is highly disputable. However, it is expected that introducing common specifications for road markings and signs will be inevitable in the future when autonomous vehicles will become more common.

[1] DIRECTIVE (EU) 2019/1936 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2019- amending Directive 2008/96/EC on road infrastructure safety management

CONTENT

1. INTRODUCTION

Road markings and signs are a fundamental element of road infrastructure as their main task is to provide timely and necessary information to the driver related to the upcoming situation. Put differently, they warn and inform drivers about the conditions and construction characteristics of the road, guide road users through the traffic network and regulate traffic in a safe way. Recently, road markings and signs have also become important for different vehicle systems, such as Advanced Driver Assistance Systems (ADAS).

When looking at road markings and signs, their effectiveness, for both humans and ADAS systems, depends on a several characteristics such as geometric, performance, operational etc. Generally, their use has been to some extent unified with the United Nation treaty on Road Signs and Signals from 1968. However, inconsistency between EU Member States still exist. In general, literature recognizes different ergonomic principles but most of the studies emphasize between three and five main ones: standardisation, compatibility, familiarity, simplicity and meaningfulness (Ben-Bassat, 2019; Ben-Bassat & Shinar, 2006; Ng & Chan, 2007; Yuan et al., 2014). Although these features are the main ones for the human driver, some of them (such as standardisation) may also play a significant role for the detectability and readability of different vehicle technologies.

Except the aforementioned ergonomic principles, performance characteristics, such as daytime and night-time visibility, chromaticity or colour contrast, play an important role in detection and readability of road markings and signs by humans and vehicles. Namely, in low visibility weather conditions (night, rain, fog etc.), these characteristics enable road markings and signs to “stand out” from the surrounding and thus be visible and comprehendible.

Although both the private sector and the national authorities in each Member State are pushing towards improving the overall quality of road markings and road signs, at least in some cases further efforts are needed. Current standards regarding road markings and road signs are based on human needs and to some extent may not be sufficient for the automated driver assistance systems (ADAS). Thus, a broader approach focusing on the needs and requirements of both human drivers and advanced vehicle systems is needed.

1.1. Purpose & scope

The analysis of current practices (carried out in WP1) revealed that road markings and road signs in Member States are regulated through national regulations, guidelines, specifications or standards. However, their performance level, i.e. quality characteristics as well as dimension and design differ among member states. Additionally, the results of a comprehensive literature analysis indicated that current standards for visibility of road markings, in some countries, may not be adequate for both human drivers and ADAS in all conditions.

Based on these insights the consortium identified an initial list of areas for which improvements could be considered. Through further work with the EGRIS experts, a narrowed list of areas regarding road marking width and visibility performance has been identified for further analysis. In order to further evaluate the potential and validity of the detailed options to be envisaged for each area, the consortium has carried out a socioeconomic assessment to estimate the costs and benefits for Member States associated with establishing minimum levels for road marking width and visibility performance for new road markings on motorways and primary roads. This report describes the results of this socioeconomic assessment. Therefore, the purpose of this report is to develop a preliminary cost information and estimate the potential benefit to cost ratio of improving road marking width and visibility performance for new road markings on motorways and primary roads.

The results of this assessment support the Commission and the Member States' experts in considering whether it is effective, desirable and feasible to implement a common approach in this field, possibly through common technical specifications or guidelines for new road markings on motorways and primary roads in the future.

2. BREAK-EVEN COST-BENEFIT ANALYSIS APPROACH

The economic appraisal approach that is applied to develop a preliminary cost information and estimate the potential benefit to cost ratio of establishing common specifications for road marking width and visibility performance is a break-even cost-benefit analysis.

A break-even cost-benefit analysis estimates the additional costs of the intervention and calculates how effective the intervention would need to be in reducing the number of crashes or injuries in order for the saved societal crash cost to weigh up against the intervention costs. This economic appraisal approach provides an idea of how 'effective' the measure should be to be 'worth' investing in. As shown in the figure 1, the break-even point is the point where the cost of the investment is equal to the societal benefit it delivers.

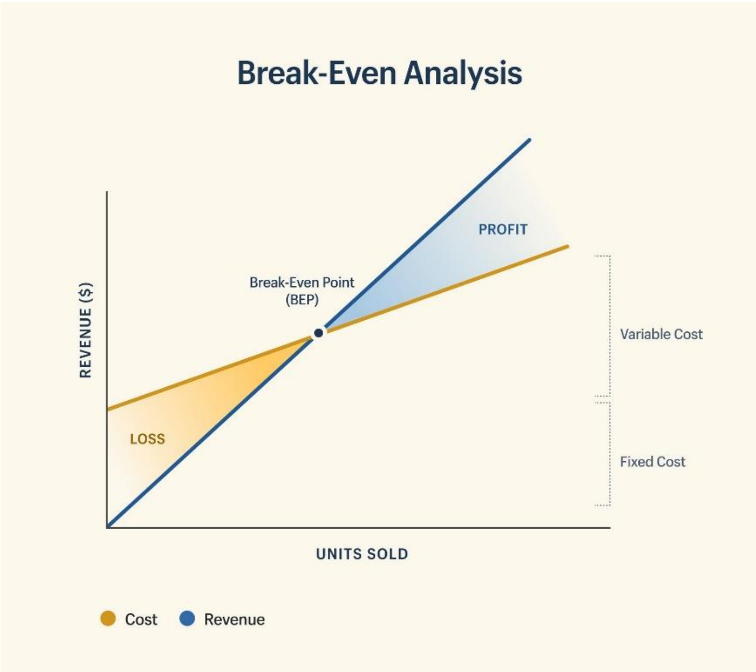

Figure 1: illustration of the break-even point

In this study, the variables in the above graph correspond to the following:

- The costs represent the costs associated with implementing common specifications for road marking width and visibility performance
- The revenues represent the benefits (saved costs) associated with implementing common specifications for road marking width and visibility performance in terms of saved lives, severely or slightly injured road users.

In this study, the intervention/measure corresponds to implement road markings with a certain width and visibility performance. The costs are expressed as the implementation costs in terms of the material costs necessary to apply road markings of certain visibility levels and width on motorways and primary roads in a certain Member State. These implementation costs take a service life (expectable life time in years) of 4 years into account:

*Length of centre + edge line markings (km) on motorways (primary roads) * (unit price of certain marking width, material and visibility level including service life over a 4-year period)*

The benefits are expressed as the number of fatal injuries, serious or slight injuries that improved road marking of certain visibility levels and width in a Member State should save over 4 years in order to be effective and efficient to be implemented.

As a result the break-even point is calculated by dividing the costs component by the benefit component: $\frac{Material\ costs\ with\ a\ service\ life\ of\ 4\ years}{\text{Unit costs of a single fatal,serious and slight injured person in each Member State}}$

The more casualties a measure needs to save to reach the break-even point, the least cost-effective the measure is.

The advantage of this approach is that it is only necessary to quantify the cost side of the cost-benefit analysis. To illustrate, societal costs figures for different injury severities are used to quantify by how much the number of injuries should decrease when applying the measure to overturn the costs. Therefore, there is no need to identify target crash types, use crash data or crash modification factors (CMFs). This advantage is illustrated by the following example:

Suppose the cost of applying the measure is in total 100 million euro and the benefit to society of saving one fatal crash equals 2 million euro, then the measure should save at least 50 fatal crashes to overturn the additional cost of applying the measure.

A disadvantage of this approach is that it is difficult to decide whether it is realistic or not to save 50 fatal crashes by implementing the measure or intervention. The only way to know this, is by doing a detailed benefit calculation based on target crashes and CMFs. Therefore, the results of this break-even analysis are an overestimation of the required effectiveness of improved road markings since it assumes that this measure would have an impact on all possible crashes and injuries on motorways and primary roads.

2.1. Area of application

The break-even cost-benefit analysis is carried out on all target crashes on European motorways and primary roads on which improved road marking can have an effect. As the road safety situation and specifications of road markings differ per Member State, the analysis is carried out on a Member State level (i.e., for each Member State separately). In this study, improved road marking is defined as road markings of a higher visibility and/or width than the current situation in each Member State. Furthermore, the focus of the break-even cost-benefit analysis lies on **new** road markings on European motorways and primary roads. Given that the RISM directive does not address maintenance of existing infrastructure, the latter was not in scope of this exercise.

2.2. Road safety measures

As agreed, upon during the EGRIS-meeting of December 15th, 2021 the break-even cost-benefit analysis is calculated for the following road marking widths and visibility levels.

2.2.1. Road marking visibility

The following areas will be further analysed and undergo a break-even cost and benefit analysis in order to decide on the most appropriate option(s) of each of the following areas:

- **Area 2 - common minimal levels for daytime visibility of new road markings**
    - Run a break-even cost and benefit analysis for 100, 130 and 160 mcd*m-2*lx-1 for motorways and primary roads

- **Area 3 – common minimal levels for night-time visibility of road markings for motorways and primary roads in dry conditions**

    - For motorways: run a break-even cost-benefit analysis on the following options: (a) 300 mcd*m^{-2}*lx^{-1}, (b) 200 mcd*m-2*lx^{-1}, (c) 150 mcd*m^{-2}*lx^{-1}

    - For primary roads: run a break-even cost-benefit analysis on the following options: (a) 200 mcd*m^{-2}*lx^{-1}, (b) 150 mcd*m^{-2}*lx^{-1}

- **Area 4 - common minimal levels for night-time visibility of new road markings in wet conditions**

    - Run a break-even cost-benefit analysis for 35 and 50 for mcd*m^{-2}*lx^{-1} for motorways and primary roads

2.2.2. Road marking width

The following area will be further analysed and undergo a break-even cost and benefit analysis in order to decide on the most appropriate option(s):

- **Area 5 - common minimal width of road markings:**

    - For motorways: run a break-even cost-benefit analysis on the following options: (a) 15 cm/20 cm (centre lines/edge lines), (b) 15cm/15cm (centre lines/edge lines).

    - For primary roads, run a break-even cost-benefit analysis for 12cm/12cm (centre lines /edge lines)

2.3. Cost components

The cost components of the break-even cost benefit analysis consist of the following parameters:

- The costs to implement road markings of certain visibility levels and width taking the service life (expectable life time in years) into account. These costs are expressed as unit prices of several materials (Paint, Coldspray Plastic, ColdPlastic, Thermoplastic) and implementation options (flatline vs. structured). These costs have been sourced from the industry (SWARCO GmbH). See annex 1.1 for an overview.

- The length in km of edge lines and centre lines on motorways and primary roads in each Member State. These lengths are estimated by the Member States' experts and are retrieved from the survey data of WP1. See annex 1.2 for an overview.

- The current situation regarding road marking width and visibility levels on motorways and primary roads of each Member State. These values are provided by the Member States' experts and are retrieved from the survey data of WP1. See annex 1.3 for an overview.

2.4. Benefit components

The benefit component of the break-even cost benefit analysis consists of the following parameter:

- The unit costs of a single fatal, serious and slight injured person in each Member State. These costs have been sourced from Safetycube deliverable (D3.2)(Wijnen et al., 2017). The costs used in D3.2 originate from 2015. These costs/prices are converted to 2022 prices based on the current inflation level (June 2022) obtained from Eurostat (2022) and Inflation.eu (2022). For this purpose, the average harmonized index of consumer prices (HICP) is used as Eurostat uses this index to compare inflation in countries belonging to the European Union. The HICP represents a 'basket' of goods and services representative of the Eurozone. See annex 1.4 for an overview.

2.5. Assumptions in CBA

The key assumptions underpinning the break-even cost benefit analysis include:

- The costs and benefits are only calculated for new road markings on European motorways and primary roads.

- The break-even cost-benefit analysis is conducted for a period of four years because the average service life of the road markings is set equal to four years. The reason for this is that four years is the expectable life time of the most expensive material for which cost values are available (i.e., thermoplastic flatline road marking).

- The unit costs provided by the industry make a distinction between different materials that can be used to meet the common minimal visibility and width levels of road markings. In the break-even cost-benefit analysis we take the use of different materials to reach a certain visibility or width level into account as the material type influences the cost component. But the main focus lies on the visibility and width performance of road markings. Therefore, the purpose of this analysis is not to advise Member States on which material they should use. This decision is left to the Member States. This analysis simply provides an overview of the different possibilities that can be used to reach a certain visibility or width level.

- The costs and benefits are only calculated for Member States that do not yet meet the common minimal visibility levels of road markings during night-time (dry + wet), day-time (dry) and/or the common minimal width levels. In other words, Member States that currently apply higher width and visibility criteria or meet these criteria already are excluded from the analysis.

- In case a Member State currently applies a higher road marking width (than the common minimal defined road marking width) with a lower visibility level (than the common minimal defined visibility levels), the currently applied road marking width is kept in the break-even cost benefit analysis and combined with the common minimal defined visibility levels which the Member State currently does not meet.

- In case a Member State currently applies higher road marking visibility levels or already meets the common minimal defined road marking visibility levels but has a road marking width that is lower than the common minimal defined width levels, the currently applied road marking visibility level is kept in the break-even cost benefit analysis and combined with the common minimal defined width levels which the Member State currently does not meet.

- Some Member States also provided more than one visibility or width level to describe the current situation on their motorway and primary road network. In that case the consortium had to make the following assumptions:

    - In case a Member State mentions two values we set the current situation equal to the lowest value provided;

    - In case a Member State mentions three values we set the current situation equal to the middle value provided.

Consequently, we use the upper bound of the costs in this analysis for the motorway or primary road network knowing that a part of the network already meets higher road marking widths the costs will then be higher than in reality but the benefits must then also be higher in order to create a beneficial effect for road safety. So, in the end, his approach is stricter for the payback effects of the measure.

- As mentioned above the average harmonized index of consumer prices (HICP) with the inflation level of June 2022 is used to convert the unit costs of a fatal, serious and slight injured person from 2015 to 2022 prices. If a Member State specific value of the HCIP is available this inflation value is used to calculate the actual prices. However, for a few Member States there is no specific inflation value available. For these Member States, the European average HCIP value of June 2022 is used to calculate the actual prices.

2.6. Limitations

The limitations of this study include:

- The costs and benefits are only calculated for Member States for which data is available:
    - For some Member States there is only partial information available about certain parameters (for example the length of edge lines and centre lines). In that case, the break-even cost-benefit data is calculated with this partial data (for example only for motorways or primary roads).
    - A Member State is excluded from the break-even cost benefit analysis in case there is no information about the current road marking visibility and/or width or the length of edge and centre lines on motorways and primary roads.
- The costs to implement road markings of certain visibility levels and width taking the service life (expectable life time in years) into account originate from only 1 supplier. Therefore, these costs should be regarded as average costs and the results of the analysis give a first indication of the expected costs and benefits.
- The costs should also be regarded as average costs since the costs of implementing road markings of certain visibility levels and width may differ depending on the economic situation per Member State. This means that some Member State will pay lower market prices whereas others will pay higher market prices to implement the same visibility and width performance levels. So, for some Member States the costs used in this analysis are an over-/underestimation of the actual prices.
- The supplier did not provide unit costs and service life information for Qd 100 and 130 $mcd*m^{-2}*lx^{-1}$, RW 35 $mcd*m^{-2}*lx^{-1}$ and R_L 150 $mcd*m^{-2}*lx^{-1}$. These visibility performance levels are therefore excluded from the analysis
- The material costs used in the calculation originate from February 2022, current prices may be influenced by changing market conditions.
- The costs used in this analysis only include material costs. Other implementation costs such as costs of traffic management / road works to apply the markings etc. are not included. The implementation costs depend on the service lifetime of the material (a shorter lifetime implies higher implementation costs over the same period of time) and the type of material itself (some materials are more time consuming to apply). The non-material related implementation costs, however, are independent of the retroreflectivity or width. In other words, the personnel costs, time necessary to implement markings etc. are independent of the retroreflectivity level or width. Hence, when comparing scenarios of different levels of

retroreflectivity or width, the non-material related implementation cost is not a decisive factor.

- As mentioned above, the average service life is set equal to 4 years (expectable life time of the most expensive material for which we have cost values (i.e. thermoplastic flatline road markings). However, markings can have a lower or longer life expectancy depending on a number of factors. It is commonly known that road markings can be damaged by winter maintenance works done by snow-ploughs, traffic density and the number of heavy vehicles, surface conditions, other normal weather influences like UV light, sand etc. These aspects are not considered in the analysis. Therefore, the results of the analysis serve as a first indication of the expected costs and benefits.

- The effect of incremental higher visibility and width levels cannot be considered. This is only possible with Crash Modification Factors (CMFs). For this study, it means that the incremental change in visibility and width levels can only be considered in the cost side but not in the benefit side without using CMFs. To illustrate, in order to include this incremental change in the benefit side we should know or find a value indicating how many crashes are caused in Europe by bad marking visibility or a too narrow marking width (which is not available). For example, we should know how many crashes can be avoided if we go from a visibility of 100 to 130 to 150 $mcd*m^{-2}*lx^{-1}$ and this incremental change can only be measured by means of CMFs if they are available. For the same reason, the analysis cannot differentiate between the costs and benefits of improved road markings for human drivers or ADAS. This is only possible with the use of CMFs.

- The break-even points for some Member States (see chapter 3 and 4) is for some injury types is higher than the number of injuries that could be retrieved from the target crash data in the CARE database. However, the crash data in the CARE database suffers from underreporting due to missing information about for instance the type of road (motorway, primary road), weather/light conditions. The consultant noticed that for most of Member States, these aspects are unknown for a portion of the single-vehicle crashes and accompanying injuries in the CARE database. Target crashes for which these aspects are unknown are left out of the analysis since it is impossible to find out the crash and injury characteristics. Therefore, it is expected the actual number of fatalities, slightly injured and severely injured is higher than reported in the CBA report.

- A final limitation of this approach is that no crash or injury data related to target crashes is used. The benefit side only consists of the unit cost per fatality, severely and slightly injured person involved in a crash. Consequently, the effects/benefits of improved road markings will be overestimated since we cannot be 100% confident that better markings will have the same effect on all these crashes and injuries. In the current analysis, a 100% effectiveness on all crashes is assumed, i.e., the improved marking reduces the target crashes to zero. This overestimation can only be further decreased by doing a detailed benefit calculation based on target crashes and CMFs. CMFs could assist in lowering the overestimation, but there are no reliable CMFs available for the Europe.Therefore, the results of this break-even analysis are an overestimation of the required effectiveness of improved road markings since it assumes that this measure would have an impact on all possible crashes and injuries on motorways and primary roads whereas in reality it is very likely that the assumed effectiveness on the target crashes is not equal to 100% but to a lower percentage.

3. MEMBER STATE RESULTS

This chapter presents the results of the break-even cost-benefit analysis per Member State. Each section starts with an overview of the current situation in the Member State, followed by the road marking measures that will be calculated, the input values that are used in the analysis and the results of the break-even cost-benefits analysis for the different road marking visibility and width criteria.

3.1. Austria

3.1.1. Current situation

3.1.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	5145	9000	14145
Primary road	Not available. Austria has no definition of primary roads		
Source: WP1 survey			

3.1.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20/30	15
Primary road	Not available. Austria has no definition of primary roads	
Note: 30 cm edge line at exits and entries; 2 – Expressways (2+2 and 2+1 lane roads); 3 – On the suburban and main urban and suburban motorways the module is: 25-15-25, on suburban secondary and urban traffic and neighbourhood the module is: 15-12-15, while on local roads (urban and extra-urban) the module is: 12-10-12.		
Source: WP1 survey		

3.1.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	Not available. Austria has no definition of primary roads.
Night-time: wet (RW)	35	
Day-time: dry (Qd)	100/130	
Source: WP1 survey		

3.1.2. Road marking measures to be calculated

Austrian ***motorways*** already meet the visibility criteria for R_L (200), RW (35) and Qd (100/130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common defined visibility criteria of R_L 300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for Qd it is unclear how many motorways meet 100 or 130. Therefore, it is assumed that Qd is currently equal to the lowest value of 100 for the entire motorway network.

Furthermore, for the marking widths it is unclear how many edge lines meet a width of 20 or 30 cm. Therefore, it is assumed that the *edge line* width for the entire motorway network is currently equal to the lowest value provided namely 20 cm. As a result, the marking widths on the motorway network of 15 cm for centre lines and 20 cm for edge lines already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

The measures are only calculated for motorways since Austria has no definition for ***primary roads***.

Therefore, the break-even cost-benefit analysis is calculated for motorways only and for the following measures:

- R_L 300 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines

3.1.3. Input values for break-even cost-benefit analysis

3.1.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	3.014.655,00	3.203.975,33
Serious injury	381.285,00	405.229,70
Slight injury	26.880,00	28.568,06
The average harmonised inflation of Austria in 2022: 6.28% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.1.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.1.4. Break-even cost-benefit analysis results

- **Motorways: R_L 300/RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 13.737.600,00	€ 7.754.400,00	€ 9.315.000,00	€ 12.231.000,00	€ 10.800.000,00
20 cm edge line	€ 10.471.104,00	€ 5.910.576,00	€ 7.100.100,00	€ 9.322.740,00	€ 8.232.000,00
Total	€ 24.208.704,00	€ 13.664.976,00	€ 16.415.100,00	€ 21.553.740,00	€ 19.032.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 3.203.975,33	€ 405.229,70	€ 28.568,06		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	8	4	5	7	6
Severely injured	60	34	41	53	47
Slightly injured	847	478	575	754	666
Average break-even point: cost/benefits					
Fatally injured	6 fatalities				
Severely injured	47 severely injured				
Slightly injured	664 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 60 seriously injured **or** 847 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 34 seriously injured **or** 478 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 5 fatally injured **or** 41 seriously injured **or** 575 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 7 fatally injured **or** 53 seriously injured **or** 754 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 6 fatally injured **or** 47 seriously injured **or** 666 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 6 fatally injured **or** 47 seriously injured **or** 664 slightly injured road users over a 4-year period.

- **Motorways: Qd 130 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.

3.2. Belgium

3.2.1. Current situation

3.2.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	Only input received for Wallonia		
Primary road	Only input received for Wallonia		
Source: WP1 survey			

3.2.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	20
Primary road	20	15
Source: WP1 survey		

3.2.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	25	Not requested
Day-time: dry (Qd)	160/130	160/130
Source: WP1 survey		

3.2.2. Road marking measures to be calculated

Belgian ***motorways*** already meet the visibility criteria for R_L (150) and Qd (160/130) but do not meet the common visibility criteria of R_L 200/300 and RW 35/50 mcd*m^{-2}*lx^{-1}. However, for Qd it is unclear how many motorways meet 160 or 130 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 for the entire motorway network. Furthermore, the marking widths on the motorway network of 20 cm for centre lines and 30 cm for edge line are currently higher than the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 20 cm for centre lines and 30 cm for edge lines

Belgian ***primary roads*** already meet the visibility criteria for R_L (150) and Qd (160/130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200 and RW 35/50 mcd*m^{-2}*lx^{-1}. However, for Qd it is unclear how many primary roads meet 160 or 130 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 mcd*m^{-2}*lx^{-1} for the entire primary road network. Furthermore, the marking widths on the primary road network of 15 cm for centre lines and 20 cm for edge lines are currently higher than the criteria set in the study namely 12 cm for edge and centre lines.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines

3.2.3. Input values for break-even cost-benefit analysis

3.2.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.021.091,00	2.209.456,68
Serious injury	307.364,00	336.010,32
Slight injury	19.766,00	21.608,19
The average harmonised inflation of Belgium in 2022: 9.32% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.2.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00
30 cm	€ 1.418,40	€ 973,50	€ 1.710,00

3.2.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads.

3.3. Bulgaria

3.3.1. Current situation

3.3.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	3200	1600	4800
Primary road	6000	3000	9000
Source: WP1 survey			

3.3.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	15
Primary road	15	10
Source: WP1 survey		

3.3.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.3.2. Road marking measures to be calculated

Bulgarian ***motorways*** already meet the highest visibility criteria set for Qd, R_L and RW in this study. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 25 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, **no break-even cost benefit analysis** for Bulgarian motorways is calculated.

Bulgarian ***primary roads*** already meet the highest visibility criteria set for Qd, R_L and RW in this study. Furthermore, the edge line width (15 cm) is higher than the criteria set in the study namely 12 cm. However, the centre line width (10 cm) is lower than the criteria set in the study namely 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 15 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 15 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 15 cm for edge lines

3.3.3. Input values for break-even cost-benefit analysis

3.3.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.355.315,00	1.447.205,36
Serious injury	220.390,00	235.332,44
Slight injury	57.267,00	61.149,70
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Bulgaria Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.3.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00

3.3.4. Break-even cost-benefit analysis results

- **Primary roads: R_L 300/RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre lines	€ 3.663.360	€ 2.067.840	€ 2.484.000	€ 3.261.600	€ 2.880.000
15 cm edge lines	€ 9.158.400	€ 5.169.600	€ 6.210.000	€ 8.154.000	€ 7.200.000
Total	€ 12.821.760	€ 7.237.440	€ 8.694.000	€ 11.415.600	€ 10.080.000
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.447.205,36	€ 235.332,44	€ 61.149,70		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	9	5	6	8	7
Severely injured	54	31	37	49	43
Slightly injured	210	118	142	187	165
Average break-even point: cost/benefits					
Fatally injured	7 fatalities				
Severely injured	43 severely injured				
Slightly injured	164 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 9 fatally injured **or** 54 seriously injured **or** 210 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 31 seriously injured **or** 118 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 6 fatally injured **or** 37 seriously injured **or** 142 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 49 seriously injured **or** 187 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 7 fatally injured **or** 43 seriously injured **or** 165 slightly injured road users over a 4-year period.
- Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 7 fatally injured **or** 43 seriously injured **or** 164 slightly injured road users over a 4-year period.

3.4. Croatia

3.4.1. Current situation

3.4.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	17238	8638	25876
Primary road	10763	7175	17938
Source: WP1 survey			

3.4.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	20
Primary road	12/15	12/15
Source: WP1 survey		

3.4.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	200
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	160	130
Source: WP1 survey		

3.4.2. Road marking measures to be calculated

The road markings on ***motorways*** in Croatia meet the visibility and width levels recommended by the study or have higher visibility and width levels in place. As a result, there is no need to calculate a break-even cost-benefit analysis.

Croatian ***primary roads*** meet the visibility criteria for R_L (200), RW (50) and Qd (130) mcd*m^{-2}*lx^{-1}, but do not meet the common visibility criterion of Qd 160 mcd*m^{-2}*lx^{-1}. The marking width also meets the recommendation of 12 cm for edge and centre lines. On some parts of the network the width is equal to 15 cm. However, it is unclear which parts of the network have a marking width of 12 or 15 cm. Therefore, it is assumed that the edge and centre line width for the entire network is equal to 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measure:

- Qd 160 mcd*m^{-2}*$lx^{-1}$with 12 cm for centre lines and 12 cm for edge lines

3.4.3. Input values for break-even cost-benefit analysis

3.4.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.230.967,00	2.382.226,56
Serious injury	290.042,00	309.706,85
Slight injury	22.259,00	23.768,16
The average harmonised inflation of Europe in 2022: 6.78%*		
*Note: European average used since there is no specific HICP value available for Croatia		
Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.4.3.2. Unit costs of road marking materials including service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00

3.4.4. *Break-even cost-benefit analysis results*

- **Primary roads: Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre + edge lines	€ 21.904.450,56	€ 12.364.304,64	€ 14.852.664,00	€ 19.502.193,60	€ 17.220.480,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.382.226,56	€ 309.706,85	€ 23.768,16		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	9	5	6	8	7
Severely injured	71	40	48	63	56
Slightly injured	922	520	625	821	725
Average break-even point: cost/benefits					
Fatally injured	7 fatalities				
Severely injured	55 severely injured				
Slightly injured	722 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 9 fatally injured **or** 71 seriously injured **or** 922 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 40 seriously injured **or** 520 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 6 fatally injured **or** 48 seriously injured **or** 625 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 63 seriously injured **or** 821 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 7 fatally injured **or** 56 seriously injured **or** 725 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 7 fatally injured **or** 55 seriously injured **or** 722 slightly injured road users over a 4-year period.

3.5. Cyprus

3.5.1. Current situation

3.5.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.5.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	20
Primary road	10/15	10/15
Source: WP1 survey		

3.5.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.5.2. Road marking measures to be calculated

Motorways in Cyprus meet the visibility criteria for R_L (200), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 20 cm for centre lines and edge lines already meet or are higher than the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$with 20 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 20 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$with 20 cm for centre lines and 20 cm for edge lines

Primary roads in Cyprus meet the visibility criteria for R_L (200), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge and centre lines meet a width of 10 or 15 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. As a result, the current edge and centre line width (10 cm) is lower than criteria set in the study namely 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- RW 50 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 12 cm for edge lines

3.5.3. Input values for break-even cost-benefit analysis

3.5.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.027.088,00	1.096.724,57
Serious injury	135.535,00	144.724,27
Slight injury	9.921,00	10.593,64
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Cyprus Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.5.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

3.5.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads.

3.6. Estonia

3.6.1. Current situation

3.6.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No roads classified as motorways		
Primary road	No data delivered		
Source: WP1 survey			

3.6.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20/30	15
Primary road	10/15/20/30	10/15
Source: WP1 survey		

3.6.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.6.2. Road marking measures to be calculated

Estonia has no roads classified as ***motorways*** so there is no need to calculate a break-even cost-benefit analysis for road marking width and visibility levels on motorways.

Primary roads in Estonia meet the visibility criteria for R_L (150), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria for R_L 200, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge lines meet a width of 10, 15, 20 or 30 cm and how many centre lines meet a width of 10 or 15 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. As a result, the current edge and centre line width (10 cm) is lower than criteria set in the study namely 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 12 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 12 cm for edge lines

3.6.3. Input values for break-even cost-benefit analysis

3.6.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.819.426,00	3.010.583,08
Serious injury	959.011,00	1.024.031,95
Slight injury	36.802,00	39.297,18
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Estonia Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.6.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / RL 300 / Qd 160 $mcd*m^{-2}*lx^{-1}$					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00

RL 200 / Qd 160 mcd*m-2*lx-1			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00

3.6.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on primary roads.

3.7. Finland

3.7.1. Current situation

3.7.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	3700	1900	5600
Primary road	26000	13000	39000
Source: WP1 survey			

3.7.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	10
Primary road	10	10
Note: Centre line can be 30 cm or 40 cm (or 60 cm) on motorway weaving sections. Edge line can be 30 cm or 40 cm on primary roads or motorway weaving sections and even up to 60 cm on motorway weaving sections.		
Source: WP1 survey		

3.7.1.3. Road marking visibility

	Motorway (mcd*m-2*lx-1)	Primary road (mcd*m-2*lx-1)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	Not requested	Not requested
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.7.2. Road marking measures to be calculated

Finnish ***motorways*** already meet the visibility criteria for R_L (150) and Qd (130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200/300, RW 35/50 and Qd 160 mcd*m^{-2}*lx^{-1}. Currently, Finland applies a width of 10 cm for centre lines. This width is lower than the common width criterion of 15 cm. The currently applied edge line width of 20 cm meets the common width criterion of 20 cm set in this study.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines

Finnish ***primary roads*** already meet the visibility criteria for R_L (150) and Qd (130) mcd*m^{-2}*lx^{-1}but do not meet the common visibility criteria of R_L 200, RW 35/50 and Qd 160 mcd*m^{-2}*lx^{-1}. Currently, Finland applies a width of 10 cm for edge and centre lines. This width is lower than the commonly defined width criterion of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 12 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 12 cm for edge lines

3.7.3. *Input values for break-even cost-benefit analysis*

3.7.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.340.452,00	2.468.006,63
Serious injury	671.383,00	707.973,37
Slight injury	29.111,00	30.697,55
The average harmonised inflation of Finland in 2022: 5.45% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.7.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.7.4. Break-even cost-benefit analysis results

- **Motorways: R_L 200 (mcd*m^{-2}*lx$^{-1)}$ with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 1.347.480,00	€ 924.825,00	€ 1.624.500,00
20 cm edge line	€ 3.498.720,00	€ 2.401.300,00	€ 4.218.000,00
Total	€ 4.846.200,00	€ 3.326.125,00	€ 5.842.500,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.468.006,63	€ 707.973,37	€ 30.697,55
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2	1	2
Severely injured	7	5	8
Slightly injured	158	108	190
Average break-even point: cost/benefits			
Fatally injured	2 fatalities		
Severely injured	7 severely injured		
Slightly injured	152 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 7 seriously injured **or** 158 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 1 fatally injured **or** 5 seriously injured **or** 108 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 8 seriously injured **or** 190 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 7 seriously injured **or** 152 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/RW 50/Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 2.900.160,00	€ 1.637.040,00	€ 1.966.500,00	€ 2.582.100,00	€ 2.280.000,00
20 cm edge line	€ 7.530.240,00	€ 4.250.560,00	€ 5.106.000,00	€ 6.704.400,00	€ 5.920.000,00
Total	€ 10.430.400,00	€ 5.887.600,00	€ 7.072.500,00	€ 9.286.500,00	€ 8.200.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.468.006,63	€ 707.973,37	€ 30.697,55		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	4	2	3	4	3
Severely injured	15	8	10	13	12
Slightly injured	340	192	230	303	267
Average break-even point: cost/benefits					
Fatally injured	3 fatalities				
Severely injured	12 severely injured				
Slightly injured	266 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 15 seriously injured **or** 340 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 8 seriously injured **or** 192 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 10 seriously injured **or** 230 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 13 seriously injured **or** 303 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 12 seriously injured **or** 267 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 3 fatally injured **or** 12 seriously injured **or** 266 slightly injured road users over a 4-year period.

- **Motorways: RW 35 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 $mcd*m^{-2}*lx^{-1}$. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 $mcd*m^{-2}*lx^{-1}$. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 $mcd*m^{-2}*lx^{-1}$ differs.

- **Primary roads: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm centre + edge line	€ 22.127.040,00	€ 15.186.600,00	€ 26.676.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.468.006,63	€ 707.973,37	€ 30.697,55
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	9	6	11
Severely injured	31	21	38
Slightly injured	721	495	869
Average break-even point: cost/benefits			
Fatally injured	9 fatalities		
Severely injured	30 severely injured		
Slightly injured	695 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 9 fatally injured **or** 31 seriously injured **or** 721 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 6 fatally injured **or** 21 seriously injured **or** 495 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 11 fatally injured **or** 38 seriously injured **or** 869 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 9 fatally injured **or** 30 seriously injured **or** 695 slightly injured road users over a 4-year period.

- **Primary roads: RW 35 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 12 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 $mcd*m^{-2}*lx^{-1}$. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW

50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre + edge line	€ 47.623.680,00	€ 26.881.920,00	€ 32.292.000,00	€ 42.400.800,00	€ 37.440.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.468.006,63	€ 707.973,37	€ 30.697,55		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	19	11	13	17	15
Severely injured	67	38	46	60	53
Slightly injured	1.551	876	1.052	1.381	1.220
Average break-even point: cost/benefits					
Fatally injured	15 fatalities				
Severely injured	53 severely injured				
Slightly injured	1.216 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 19 fatally injured **or** 67 seriously injured **or** 1.551 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 11 fatally injured **or** 38 seriously injured **or** 876 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 13 fatally injured **or** 46 seriously injured **or** 1.052 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 17 fatally injured **or** 60 seriously injured **or** 1.381 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 15 fatally injured **or** 53 seriously injured **or** 1.220 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 15 fatally injured **or** 53 seriously injured **or** 1.216 slightly injured road users over a 4-year period.

3.8. France

3.8.1. Current situation

3.8.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	46600	42200	88800
Primary road	26500	13500	40000
Source: WP1 survey			

3.8.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	22.5	15
Primary road	18/22.5	12/15
Note : Non motorway dual carriageways" - centre line: 15cm, edge line: 22,5 cm; ** "Single carriageways" - centre line: 12 cm, edge line: 18 cm		
Source: WP1 survey		

3.8.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	100/130	100/130
Source: WP1 survey		

3.8.2. Road marking measures to be calculated

French ***motorways*** already meet the visibility criteria for R_L (150) and Qd (100/130) mcd*m^{-2}*lx^{-1}but do not meet the common visibility criteria of R_L 200/300, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. Furthermore, RW 35 is currently very little used are very little used on motorways. However, for Qd it is unclear how many motorways meet 100 or 130. Therefore, it is assumed that Qd is currently equal to the lowest value of 100 mcd*m^{-2}*lx^{-1} for the entire motorway network. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 22.5 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 22.5 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 22.5 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 22.5 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 22.5 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 22.5 cm for edge lines

- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 22.5 cm for edge lines

French ***primary roads*** already meet the visibility criteria for R_L (150) andQd (100/130) mcd*m^{-2}*lx^{-1}but do not meet the common visibility criteria of R_L 200, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. Furthermore, RW 35 is currently very little used are very little used on primary roads. However, for Qd it is unclear how many primary roads meet 100 or 130 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 100 mcd*m^{-2}*lx^{-1}for the entire primary road network. Furthermore, for the marking widths it is unclear how many primary roads meet 12/15 cm for centre lines and 18/22.5 cm for edge lines. Therefore, it is assumed that the width is currently equal to the lowest width value provided for centre and edge lines for the entire primary road network. As a result, the marking widths on the primary road network of 12 cm for centre lines and 18 cm for edge lines are currently higher than or already meet the criteria set in the study namely 12 cm for edge lines and 12 cm for centre lines.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 18 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 18 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 18 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 12 cm for centre lines and 18 cm for edge lines

3.8.3. Input values for break-even cost-benefit analysis

3.8.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.944.662,00	3.084.533,45
Serious injury	368.029,00	385.510,38
Slight injury	14.070,00	14.738,33
The average harmonised inflation of France in 2022: 4.75% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.8.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
18 cm	€ 1.831,68	€ 1.033,92	€ 1.242,00	€ 1.630,80	€ 1.440,00
22,5 cm	€ 2.289,60	€ 1.292,40	€ 1.552,50	€ 2.038,50	€ 1.800,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
18 cm	€ 851,04	€ 584,10	€ 1.026,00
22,5 cm	€ 1.063,80	€ 730,13	€ 1.282,50

3.8.4. Break-even cost-benefit analysis results

- **Motorways: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 29.928.240,00	€ 20.540.850,00	€ 36.081.000,00
22,5 cm edge line	€ 49.573.080,00	€ 34.024.058,00	€ 59.764.500,00
Total	€ 79.501.320,00	€ 54.564.908,00	€ 95.845.500,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 3.084.533,45	€ 385.510,38	€ 14.738,33
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	26	18	31
Severely injured	206	142	249
Slightly injured	5.394	3.702	6.503
Average break-even point: cost/benefits			
Fatally injured	25 fatalities		
Severely injured	199 severely injured		
Slightly injured	5.200 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 26 fatally injured **or** 206 seriously injured **or** 5.394 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 18 fatally injured **or** 142 seriously injured **or** 3.702 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 31 fatally injured **or** 249 seriously injured **or** 6.503 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 25 fatally injured **or** 199 seriously injured **or** 5.200 slightly injured road users over a 4-year period.

- **Motorways: R$_L$ 300/RW 50/ Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 64.414.080,00	€ 36.359.520,00	€ 43.677.000,00	€ 57.349.800,00	€ 50.640.000,00
22,5 cm edge line	€ 106.695.360,00	€ 60.225.840,00	€ 72.346.500,00	€ 94.994.100,00	€ 83.880.000,00
Total	€ 171.109.440,00	€ 96.585.360,00	€ 116.023.500,00	€ 152.343.900,00	€ 134.520.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 3.084.533,45	€ 385.510,38	€ 14.738,33		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	55	31	38	49	44
Severely injured	444	251	301	395	349
Slightly injured	11.610	6.553	7.872	10.337	9.127
Average break-even point: cost/benefits					
Fatally injured	43 fatalities				
Severely injured	348 severely injured				
Slightly injured	9.100 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 55 fatally injured **or** 444 seriously injured **or** 11.610 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 31 fatally injured **or** 251 seriously injured **or** 6.553 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 38 fatally injured **or** 301 seriously injured **or** 7.872 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 49 fatally injured **or** 395 seriously injured **or** 10.337 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 44 fatally injured **or** 349 seriously injured **or** 9.127 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 43 fatally injured **or** 384 seriously injured **or** 9.100 slightly injured road users over a 4-year period.

- **Motorways: RW 35 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Motorways: Qd 130 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 22.5 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.

- **Primary roads: RL 200 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm centre line	€ 7.659.360,00	€ 5.256.900,00	€ 9.234.000,00
18 cm edge line	€ 22.552.560,00	€ 15.478.650,00	€ 27.189.000,00
Total	€ 30.211.920,00	€ 20.735.550,00	€ 36.423.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 3.084.533,45	€ 385.510,38	€ 14.738,33
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	10	7	12
Severely injured	78	54	94
Slightly injured	2.050	1.407	2.471
Average break-even point: cost/benefits			
Fatally injured	9 fatalities		
Severely injured	76 severely injured		
Slightly injured	1.976 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 10 fatally injured **or** 78 seriously injured **or** 2.050 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 7 fatally injured **or** 54 seriously injured **or** 1.407 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 12 fatally injured **or** 94 seriously injured **or** 2.471 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 9 fatally injured **or** 76 seriously injured **or** 1.976 slightly injured road users over a 4-year period.

- **Primary roads: RW 35 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre line	€ 16.485.120,00	€ 9.305.280,00	€ 11.178.000,00	€ 14.677.200,00	€ 12.960.000,00
18 cm edge line	€ 48.539.520,00	€ 27.398.880,00	€ 32.913.000,00	€ 32.913.000,00	€ 38.160.000,00
Total	€ 65.024.640,00	€ 36.704.160,00	€ 44.091.000,00	€ 47.590.200,00	€ 51.120.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 3.084.533,45	€ 385.510,38	€ 14.738,33		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	21	12	14	15	17
Severely injured	169	95	114	123	133
Slightly injured	4.412	2.490	2.992	3.229	3.469
Average break-even point: cost/benefits					
Fatally injured	17 fatalities				
Severely injured	132 severely injured				
Slightly injured	3.458 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 21 fatally injured **or** 169 seriously injured **or** 4.412 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 12 fatally injured **or** 95 seriously injured **or** 2.490 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 14 fatally injured **or** 114 seriously injured **or** 2.992 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 15 fatally injured **or** 123 seriously injured **or** 3.229 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 17 fatally injured **or** 133 seriously injured **or** 3.469 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 17 fatally injured **or** 132 seriously injured **or** 3.458 slightly injured road users over a 4-year period.

- **Primary roads: Qd 130 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 18 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 mcd*m^{-2}*lx^{-1}.

3.9. Germany

3.9.1. Current situation

3.9.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	43333	21667	65000
Primary road	73333	36667	110000
Source: WP1 survey			

3.9.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15/30	15
Primary road	12/25	12
Note: Motorways: left edge line 15 or 30 cm, right edge line or dashed right edge line 30 cm, dashed centre line 15 cm. National Roads: edge lines 12 cm, edge lines to separate hard shoulder/bus stops or dashed right edge line 25 cm, dashed centre marking 12 cm.		
Source: WP1 survey		

3.9.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	200/300	200/300
Night-time: wet (RW)	50/75	50/75
Day-time: dry (Qd)	160	130
Source: WP1 survey		

3.9.2. Road marking measures to be calculated

German ***motorways*** already meet or have higher visibility criteria in place for R_L (200/300), RW (50/75) and Qd (160) mcd*m^{-2}*lx^{-1}. However, for R_L it is unclear how many motorways meet 200 or 300. Therefore, it is assumed that R_L is currently equal to the lowest value of 200 mcd*m^{-2}*$lx^{-1}$for the entire motorway network. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 15 cm for edge lines or already meet the criteria set in the study namely 15 cm. However, for the edge line marking widths it is unclear how many motorways currently meet the 30 cm criterion. Therefore, it is assumed that the width is currently equal to the lowest width value provided for edge lines. As a result, the marking widths already meet the 15 cm criterion for edge lines set in the study but do not meet the 20 cm criterion.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines

German primary roads already meet or have higher visibility criteria in place for RL RW and Qd than the common defined visibility criteria. Furthermore, these primary roads also meet the common minimal width levels of 12 cm for edge and centre lines. Therefore, there is no need to calculate a break-even analysis.

3.9.3. Input values for break-even cost-benefit analysis

3.9.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.177.194,00	1.255.948,28
Serious injury	119.480,00	127.473,21
Slight injury	4.954,00	5.285,42
The average harmonised inflation of Germany in 2022: 6.69% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.9.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.9.4. Break-even cost-benefit analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 15.366.236,40	€ 10.546.412,25	€ 18.525.285,00
20 cm edge line	€ 40.975.684,80	€ 28.123.117,00	€ 49.399.620,00
Total	€ 56.341.921,20	€ 38.669.529,25	€ 67.924.905,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 1.255.948,28	€ 127.473,21	€ 5.285,42
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	45	31	54
Severely injured	442	303	533
Slightly injured	10.660	7.316	12.851
Average break-even point: cost/benefits			
Fatally injured	43 fatalities		
Severely injured	426 severely injured		
Slightly injured	10.276 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 45 fatally injured **or** 442 seriously injured **or** 10.660 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 31 fatally injured **or** 303 seriously injured **or** 7.316 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 54 fatally injured **or** 533 seriously injured **or** 12.851 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 43 fatally injured **or** 426 seriously injured **or** 10.276 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/RW 50/Qd160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 33.072.508,80	€ 18.668.287,20	€ 22.425.345,00	€ 29.445.453,00	€ 26.000.400,00
20 cm edge line	€ 88.191.321,60	€ 49.780.950,40	€ 59.799.540,00	€ 78.519.396,00	€ 69.332.800,00
Total	€ 121.263.830,40	€ 68.449.237,60	€ 82.224.885,00	€ 107.964.849,00	€ 95.333.200,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.255.948,28	€ 127.473,21	€ 5.285,42		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	97	55	65	86	76
Severely injured	951	537	645	847	748
Slightly injured	22.943	12.951	15.557	20.427	18.037
Average break-even point: cost/benefits					
Fatally injured	76 fatalities				
Severely injured	746 severely injured				
Slightly injured	17.983 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 97 fatally injured **or** 951 seriously injured **or** 22.943 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 55 fatally injured **or** 537 seriously injured **or** 12.951 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 65 fatally injured **or** 645 seriously injured **or** 15.557 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 86 fatally injured **or** 847 seriously injured **or** 20.427 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 76 fatally injured **or** 748 seriously injured **or** 18.037 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 76 fatally injured **or** 746 seriously injured **or** 17.983 slightly injured road users over a 4-year period.

3.10. Hungary

3.10.1. Current situation

3.10.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	5036	881	5917
Primary road	15674	2612	18286
Source: WP1 survey			

3.10.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15/20	12/15
Primary road	15	12
Source: WP1 survey		

3.10.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	150
Night-time: wet (RW)	75	50
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.10.2. Road marking measures to be calculated

Hungarian ***motorways*** already meet or have higher visibility criteria in place for R_L (200), RW (75) and Qd (130) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criteria of R_L 300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge lines meet a width of 15 or 20 cm and how many centre lines meet a width of 12 or 15 cm.

Therefore, it is assumed that the *edge line* width for the entire motorway network is currently equal to the lowest value provided namely 15 cm. This value is equal to the recommended width of 15 cm but is lower than the recommended width of 20 cm. For the current *centre line* width, we assume that the entire motorway network is currently equal to the lowest value provided namely 12 cm. This value is lower than the recommended width of 15 cm.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 15 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- RW 75 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 15 cm for edge lines

- RW 75 mcd*m^{-2}*$lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 mcd*m^{-2}*$lx^{-1}$with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*$lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines

Hungarian ***primary roads*** already meet or have higher visibility criteria in place for R_L (150), RW (55) and Qd (130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 200 and Qd 160 mcd*m^{-2}*lx^{-1}. Furthermore, the marking widths on the primary road network of 12 cm for centre lines and 15 cm for edge lines are currently higher than or already meet the criteria set in the study namely 12 cm for edge lines and 12 cm for centre lines.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*$lx^{-1}$with 12 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*$lx^{-1}$with 12 cm for centre lines and 15 cm for edge lines

3.10.3. Input values for break-even cost-benefit analysis

3.10.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.147.976,00	2.342.797,42
Serious injury	501.194,00	546.652,30
Slight injury	553,00	603,16
The average harmonised inflation of Hungary in 2022: 9.07%		
Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.10.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.10.4. Break-even cost-benefit analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 624.805,20	€ 428.826,75	€ 753.255,00
15 cm edge line	€ 3.571.531,20	€ 2.451.273,00	€ 4.305.780,00
Total	€ 4.196.336,40	€ 2.880.099,75	€ 5.059.035,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.342.797,42	€ 546.652,30	€ 603,16
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2	1	2
Severely injured	8	5	9
Slightly injured	6.957	4.775	8.388
Average break-even point: cost/benefits			
Fatally injured	2 fatalities		
Severely injured	7 severely injured		
Slightly injured	6.707 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 8 seriously injured **or** 6.957 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 1 fatally injured **or** 5 seriously injured **or** 4.775 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 9 seriously injured **or** 8.388 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 7 seriously injured **or** 6.707 slightly injured road users over a 4-year period.

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 624.805,20	€ 428.826,75	€ 753.255,00
20 cm edge line	€ 4.762.041,60	€ 3.268.364,00	€ 5.741.040,00
Total	€ 5.386.846,80	€ 3.697.190,75	€ 6.494.295,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.342.797,42	€ 546.652,30	€ 603,16
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2	2	3
Severely injured	10	7	12
Slightly injured	8.931	6.130	10.767
Average break-even point: cost/benefits			
Fatally injured	2 fatalities		
Severely injured	9 severely injured		
Slightly injured	8.609 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 10 seriously injured **or** 8.931 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 2 fatally injured **or** 7 seriously injured **or** 6.130 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 12 seriously injured **or** 10.767 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 9 seriously injured **or** 8.609 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.344.758,40	€ 759.069,60	€ 911.835,00	€ 1.197.279,00	€ 1.057.200,00
15 cm edge line	€ 7.686.950,40	€ 4.339.017,60	€ 5.212.260,00	€ 6.843.924,00	€ 6.043.200,00
Total	€ 9.031.708,80	€ 5.098.087,20	€ 6.124.095,00	€ 8.041.203,00	€ 7.100.400,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.342.797,42	€ 546.652,30	€ 603,16		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	4	2	3	3	3
Severely injured	17	9	11	15	13
Slightly injured	14.974	8.452	10.153	13.332	11.772
Average break-even point: cost/benefits					
Fatally injured	3 fatalities				
Severely injured	13 severely injured				
Slightly injured	11.737 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 17 seriously injured **or** 14.974 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 9 seriously injured **or** 8.452 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 11 seriously injured **or** 10.153 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 15 seriously injured **or** 13.332 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 13 seriously injured **or** 11.772 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 3 fatally injured **or** 13 seriously injured **or** 11.737 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.344.758,40	€ 759.069,60	€ 911.835,00	€ 1.197.279,00	€ 1.057.200,00
20 cm edge line	€ 10.249.267,20	€ 5.785.356,80	€ 6.949.680,00	€ 9.125.232,00	€ 8.057.600,00
Total	€ 11.594.025,60	€ 6.544.426,40	€ 7.861.515,00	€ 10.322.511,00	€ 9.114.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.342.797,42	€ 546.652,30	€ 603,16		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	5	3	3	4	4
Severely injured	21	12	14	19	17
Slightly injured	19.222	10.850	13.034	17.114	15.112
Average break-even point: cost/benefits					
Fatally injured	4 fatalities				
Severely injured	17 severely injured				
Slightly injured	15.066 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 21 seriously injured **or** 19.222 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 12 seriously injured **or** 10.850 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 14 seriously injured **or** 13.034 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 19 seriously injured **or** 17.114 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 4 fatally injured **or** 17 seriously injured **or** 15.112 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 4 fatally injured **or** 17 seriously injured **or** 15.066 slightly injured road users over a 4-year period.

- **Motorways: RW 75 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 75 $mcd*m^{-2}*lx^{-1}$.

- **Motorways: RW 75 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 75 $mcd*m^{-2}*lx^{-1}$.

- **Primary roads: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm centre line	€ 1.481.944,32	€ 1.017.112,80	€ 1.786.608,00
15 cm edge line	€ 11.116.000,80	€ 7.629.319,50	€ 13.401.270,00
Total	€ 12.597.945,12	€ 8.646.432,30	€ 15.187.878,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.342.797,42	€ 546.652,30	€ 603,16
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	5	4	6
Severely injured	23	16	28
Slightly injured	20.887	14.335	25.181
Average break-even point: cost/benefits			
Fatally injured	5 fatalities		
Severely injured	22 severely injured		
Slightly injured	20.134 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 23 seriously injured **or** 20.887 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 4 fatally injured **or** 16 seriously injured **or** 14.335 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 6 fatally injured **or** 28 seriously injured **or** 25.181 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 5 fatally injured **or** 22 seriously injured **or** 20.134 slightly injured road users over a 4-year period.

- **Primary roads: Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre line	€ 3.189.565,44	€ 1.800.399,36	€ 2.162.736,00	€ 2.839.766,40	€ 2.507.520,00
15 cm edge line	€ 23.924.793,60	€ 13.504.718,40	€ 16.222.590,00	€ 21.300.966,00	€ 18.808.800,00
Total	€ 27.114.359,04	€ 15.305.117,76	€ 18.385.326,00	€ 24.140.732,40	€ 21.316.320,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.342.797,42	€ 546.652,30	€ 603,16		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	12	7	8	10	9
Severely injured	50	28	34	44	39
Slightly injured	44.954	25.375	30.482	40.024	35.341
Average break-even point: cost/benefits					
Fatally injured	9 fatalities				
Severely injured	39 severely injured				
Slightly injured	35.235 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 12 fatally injured **or** 50 seriously injured **or** 44.954 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 7 fatally injured **or** 28 seriously injured **or** 25.375 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 8 fatally injured **or** 34 seriously injured **or** 30.482 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 10 fatally injured **or** 44 seriously injured **or** 40.024 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 9 fatally injured **or** 39 seriously injured **or** 35.341 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 9 fatally injured **or** 39 seriously injured **or** 35.235 slightly injured road users over a 4-year period.

3.11. Iceland

3.11.1. Current situation

3.11.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No roads classified as motorways		
Primary road	6620	4490	11110
Source: WP1 survey			

3.11.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	No roads classified as motorways	
Primary road	10	10
Source: WP1 survey		

3.11.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	No roads classified as motorways	150
Night-time: wet (RW)		Not requested
Day-time: dry (Qd)		130
Source: WP1 survey		

3.11.2. Road marking measures to be calculated

Iceland has no motorways. Therefore, the break-even cost-benefit analysis is only calculated for certain values for primary roads.

Icelandic ***primary roads*** already have visibility criteria in place for R_L (150) and Qd (130) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criteria of R_L 200, RW 35/50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the primary road network of 10 cm for centre lines and 10 cm for edge lines are currently lower than the criteria set in the study namely 12 cm for edge lines and centre lines.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 12 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 12 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$12 cm for centre lines and 12 cm for edge lines

3.11.3. Input values for break-even cost-benefit analysis

3.11.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.861.281,00	2.995.475,08
Serious injury	364.914,00	382.028,47
Slight injury	71.742,00	75.106,70
The average harmonised inflation of Iceland in 2022: 4.69% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.11.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 $mcd*m^{-2}*lx^{-1}$					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00

R_L 200 / Qd 160 $mcd*m^{-2}*lx^{-1}$			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00

3.11.4. Break-even cost-benefit analysis results

- **Primary roads: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm edge + centre lines	€ 6.303.369,60	€ 4.326.234,00	€ 7.599.240,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.995.475,08	€ 382.028,47	€ 75.106,70
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2	1	3
Severely injured	16	11	20
Slightly injured	84	58	101
Average break-even point: cost/benefits			
Fatally injured	2 fatalities		
Severely injured	16 severely injured		
Slightly injured	81 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 16 seriously injured **or** 84 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 1 fatally injured **or** 11 seriously injured **or** 58 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 20 seriously injured **or** 101 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 16 seriously injured **or** 81 slightly injured road users over a 4-year period.

- **Primary roads: RW 35 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm edge + centre lines	€ 13.566.643,20	€ 7.657.900,80	€ 9.199.080,00	€ 12.078.792,00	€ 10.665.600,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.995.475,08	€ 382.028,47	€ 75.106,70		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	5	3	3	4	4
Severely injured	36	20	24	32	28
Slightly injured	181	102	122	161	142
Average break-even point: cost/benefits					
Fatally injured	4 fatalities				
Severely injured	28 severely injured				
Slightly injured	142 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 36 seriously injured **or** 181 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 20 seriously injured **or** 102 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 24 seriously injured **or** 122 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 32 seriously injured **or** 161 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 4 fatally injured **or** 28 seriously injured **or** 142 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 24 fatally injured **or** 28 seriously injured **or** 142 slightly injured road users over a 4-year period.

3.12. Ireland

3.12.1. Current situation

3.12.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	1.888	250	2138
Primary road	4.298	4.000	8298
Source: WP1 survey			

3.12.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15	10
Primary road	15	15
Source: WP1 survey		

3.12.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	200	200
Source: WP1 survey		

3.12.2. Road marking measures to be calculated

Irish ***motorways*** already meet the visibility criteria for R_L (150), R_L (200), RW (50) and Qd (100/130/160) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 300 mcd*m^{-2}*lx^{-1}. Furthermore, the marking widths on the motorway network of 10 cm for centre lines and 15 cm for edge lines are currently lower than he criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the social cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- R_L 300 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines
- Qd 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

Irish ***primary roads*** already meet the visibility criteria for R_L (150), R_L 200, RW (50) and Qd (100/130/160) mcd*m^{-2}*lx^{-1}. Furthermore, the marking widths on the primary road network of 15 cm for centre and edge lines are currently higher than the criteria set in the study namely 12 cm for edge and centre lines. Therefore, there is no need to calculate a break-even analysis for primary roads.

3.12.3. Input values for social cost-benefit analysis

3.12.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.965.163,00	2.153.818,65
Serious injury	225.511,00	247.160,06
Slight injury	20.860,00	22.862,56
The average harmonised inflation of Ireland in 2022: 9.60% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.12.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 $mcd*m^{-2}*lx^{-1}$			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.12.4. Break-even analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 177.300,00	€ 121.687,50	€ 213.750,00
15 cm edge line	€ 1.338.969,60	€ 918.984,00	€ 1.614.240,00
Total	€ 1.516.269,60	€ 1.040.671,50	€ 1.827.990,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.153.818,65	€ 247.160,06	€ 22.862,56
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	1	0,48	1
Severely injured	6	4	7
Slightly injured	66	46	80
Average break-even point: cost/benefits			
Fatally injured	1 fatality		
Severely injured	6 severely injured		
Slightly injured	64 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 6 seriously injured **or** 66 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 0,48 fatally injured **or** 4 seriously injured **or** 46 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 7 seriously injured **or** 80 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 1 fatally injured **or** 6 seriously injured **or** 64 slightly injured road users over a 4-year period.

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 177.300,00	€ 121.687,50	€ 213.750,00
20 cm edge line	€ 1.785.292,80	€ 1.225.312,00	€ 2.152.320,00
Total	€ 1.962.592,80	€ 1.346.999,50	€ 2.366.070,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.153.818,65	€ 247.160,06	€ 22.862,56
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	1	1	1
Severely injured	8	5	10
Slightly injured	86	59	103
Average break-even point: cost/benefits			
Fatally injured	1 fatality		
Severely injured	8 severely injured		
Slightly injured	83 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 8 seriously injured **or** 86 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 1 fatally injured **or** 5 seriously injured **or** 59 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 10 seriously injured **or** 103 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 1 fatally injured **or** 8 seriously injured **or** 83 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/RW 50 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 381.600,00	€ 215.400,00	€ 258.750,00	€ 339.750,00	€ 300.000,00
15 cm edge line	€ 2.881.843,20	€ 1.626.700,80	€ 1.954.080,00	€ 2.565.792,00	€ 2.265.600,00
Total	€ 3.263.443,20	€ 1.842.100,80	€ 2.212.830,00	€ 2.905.542,00	€ 2.565.600,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.153.818,65	€ 247.160,06	€ 22.862,56		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	2	1	1	1	1
Severely injured	13	7	9	12	10
Slightly injured	143	81	97	127	112
Average break-even point: cost/benefits					
Fatally injured	1 fatality				
Severely injured	10 severely injured				
Slightly injured	112 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 13 seriously injured **or** 143 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 7 seriously injured **or** 81 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 1 fatally injured **or** 9 seriously injured **or** 97 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 12 seriously injured **or** 127 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 1 fatally injured **or** 10 seriously injured **or** 112 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 1 fatally injured **or** 10 seriously injured **or** 112 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/RW 50 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 381.600,00	€ 215.400,00	€ 258.750,00	€ 339.750,00	€ 300.000,00
20 cm edge line	€ 3.842.457,60	€ 2.168.934,40	€ 2.605.440,00	€ 3.421.056,00	€ 3.020.800,00
Total	€ 4.224.057,60	€ 2.384.334,40	€ 2.864.190,00	€ 3.760.806,00	€ 3.320.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.153.818,65	€ 247.160,06	€ 22.862,56		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	2	1	1	2	2
Severely injured	17	10	12	15	13
Slightly injured	185	104	125	164	145
Average break-even point: cost/benefits					
Fatally injured	2 fatalities				
Severely injured	13 severely injured				
Slightly injured	145 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 13 seriously injured **or** 143 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 1 fatally injured **or** 10 seriously injured **or** 104 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 1 fatally injured **or** 12 seriously injured **or** 125 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 15 seriously injured **or** 164 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 2 fatally injured **or** 13 seriously injured **or** 145 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 13 seriously injured **or** 145 slightly injured road users over a 4-year period.

- **Motorways: Qd 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 200 $mcd*m^{-2}*lx^{-1}$.

- **Motorways: Qd 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 200 $mcd*m^{-2}*lx^{-1}$.

3.13. Italy

3.13.1. Current situation

3.13.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway		No data delivered	
Primary road		No data delivered	
Source: WP1 survey			

3.13.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	15
Primary road	12/25	15
Source: WP1 survey		

3.13.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	Not requested
Night-time: wet (RW)	50	Not requested
Day-time: dry (Qd)	130	Not requested
Source: WP1 survey		

3.13.2. Road marking measures to be calculated

Italian ***motorways*** already meet the visibility criteria for R_L (150), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200/300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 25 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 25 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 25 cm for edge lines

- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 25 cm for edge lines

Italy has no set requirements for ***primary roads*** with respect to road marking visibility. The current centre line width of 15 cm is higher than the recommended width of 15 cm.

However, for the marking widths it is unclear how many edge lines meet a width of 12 or 25 cm. Therefore, it is assumed that the *edge line* width for the entire primary road network is currently equal to the lowest value provided namely 12 cm. This value is equal to the recommended width of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 12 cm for edge lines
- R_L 150 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 12 cm for edge lines
- RW 35 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 12 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 12 cm for edge lines
- Qd 100 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 12 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 12 cm for edge lines

3.13.3. Input values for break-even cost-benefit analysis-

3.13.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.615.566,00	1.717.831,33
Serious injury	211.860,00	225.270,74
Slight injury	18.245,00	19.399,91
The average harmonised inflation of Italy in 2022: 6.33% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.13.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
25 cm	€ 2.544,00	€ 1.436,00	€ 1.725,00	€ 2.265,00	€ 2.000,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
25 cm	€ 1.182,00	€ 811,25	€ 1.425,00

3.13.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads.

3.14. Latvia

3.14.1. Current situation

3.14.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No roads classified as motorways		
Primary road	No data delivered		
Source: WP1 survey			

3.14.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	No roads classified as motorways	
Primary road	10/15/20	10/15/20
Source: WP1 survey		

3.14.1.3. Road marking visibility

	Motorway (mcd*m^{-2}*lx^{-1})	Primary road (mcd*m^{-2}*lx^{-1})
Night-time: dry (R_L)	No roads classified as motorways	150
Night-time: wet (RW)		50
Day-time: dry (Qd)		100
Source: WP1 survey		

3.14.2. Road marking measures to be calculated

Latvia has no motorways. Therefore, the break-even cost-benefit analysis is only calculated for certain values for primary roads.

Latvian ***primary roads*** already meet the visibility criteria for R_L (150), RW (50) and Qd (100) mcd*m^{-2}*lx^{-1}but do not meet the common visibility criteria of R_L 200 and Qd 130/160 mcd*m^{-2}*lx^{-1}. However, for the marking widths it is unclear how many edge and centre lines meet a width of 10, 15 or 20 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the middle value provided namely 15 cm. This value is higher than the recommended width of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

3.14.3. Input values for break-even cost-benefit analysis

3.14.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.141.935,00	1.219.358,19
Serious injury	28.205,00	30.117,30
Slight injury	296,00	316,07
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Latvia Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.14.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00

3.14.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on primary roads.

3.15. Lithuania

3.15.1. Current situation

3.15.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	1720	860	2580
Primary road	2892	1446	4338
Source: WP1 survey			

3.15.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	15
Primary road	25	12
Source: WP1 survey		

3.15.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.15.2. Road marking measures to be calculated

Lithuanian ***motorways*** already meet the visibility criteria for R_L (200), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 30 cm for edge lines are currently higher than or already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines

- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines

Lithuanian ***primary roads*** already meet the visibility criteria in place for R_L (200), RW (50) and Qd (130) but do not meet the common visibility criterion of Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the primary network of 12 cm for centre lines and 25 cm for edge lines are currently higher than or equal to the criteria set in the study namely 12 cm for edge lines and 12 cm for centre lines.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measure:

- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 12 cm for centre lines and 25 cm for edge lines

3.15.3. Input values for break-even cost-benefit analysis

3.15.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	988.981,00	1.056.033,91
Serious injury	89.804,00	95.892,71
Slight injury	Not available	Not available
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Lithuania Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.15.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / RL 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
25 cm	€ 2.544,00	€ 1.436,00	€ 1.725,00	€ 2.265,00	€ 2.000,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

3.15.4. Break-even cost-benefit analysis results

- **Motorways: RL 300/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 1.312.704,00	€ 740.976,00	€ 890.100,00	€ 1.168.740,00	€ 1.032.000,00
30 cm edge line	€ 5.250.816,00	€ 2.963.904,00	€ 3.560.400,00	€ 4.674.960,00	€ 4.128.000,00
Total	€ 6.563.520,00	€ 3.704.880,00	€ 4.450.500,00	€ 5.843.700,00	€ 5.160.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.056.033,91	€ 95.892,71			
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	6	4	4	6	5
Severely injured	68	39	46	61	54
Slightly injured					
Average break-even point: cost/benefits					
Fatally injured	5 fatalities				
Severely injured	54 severely injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 6 fatally injured **or** 68 seriously injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 39 seriously injured over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 4 fatally injured **or** 46 seriously injured over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 6 fatally injured **or** 61 seriously injured over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 5 fatally injured **or** 54 seriously injured over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 5 fatally injured **or** 54 seriously injured.

The benefits could not be calculated for slightly injured because there is no unit cost available for slightly injured road users in Lithuania.

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 25 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm centre line	€ 1.765.739,52	€ 996.698,88	€ 1.197.288,00	€ 1.572.091,20	€ 1.388.160,00
25 cm edge line	€ 7.357.248,00	€ 4.152.912,00	€ 4.988.700,00	€ 6.550.380,00	€ 5.784.000,00
Total	€ 9.122.987,52	€ 5.149.610,88	€ 6.185.988,00	€ 8.122.471,20	€ 7.172.160,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 1.056.033,91	€ 95.892,71			
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	9	5	6	8	7
Severely injured	95	54	65	85	75
Slightly injured					
Average break-even point: cost/benefits					
Fatally injured	7 fatalities				
Severely injured	75 severely injured				
Slightly injured					

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 9 fatally injured **or** 95 seriously injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 54 seriously injured over a 4-year period.
- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 6 fatally injured **or** 65 seriously injured over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 85 seriously injured over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 7 fatally injured **or** 75 seriously injured over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 7 fatally injured **or** 75 seriously injured.

The benefits could not be calculated for slightly injured because there is no unit cost available for slightly injured road users in Lithuania.

3.16. Luxembourg

3.16.1. Current situation

3.16.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	1000	330	1330
Primary road	No data delivered		
Source: WP1 survey			

3.16.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	22.5	15
Primary road	12	12
Source: WP1 survey		

3.16.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	200
Night-time: wet (RW)	75	50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.16.2. Road marking measures to be calculated

The road markings on motorways and primary roads in Luxembourg already meet the visibility and width levels recommended by the study or have higher visibility and width levels in place.

As a result, there is no need to calculate a break-even cost-benefit analysis.

3.17. Netherlands

3.17.1. Current situation

3.17.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	11..058	2.146	13.204
Primary road	8.846	1.718	10.564
Source: WP1 survey			

3.17.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	15
Primary road	15/20	15
Source: WP1 survey		

3.17.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	100	100
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.17.2. Road marking measures to be calculated

Dutch ***motorways*** already meet the visibility criteria for R_L (100), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criteria of R_L 150/200/300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 20 cm for edge lines already meet the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 150 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines

- Qd 160 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 20 cm for edge lines

Dutch ***primary roads*** already meet the visibility criteria for R_L (100), RW (35) and Qd (130) mcd*m^{-2}*lx^{-1} but do not meet the common visibility criteria of R_L 150/200, RW 50 and Qd 160 mcd*m^{-2}*lx^{-1}. Furthermore, the marking widths on the primary road network of 15 cm for centre lines and 15/20 cm for edge lines are higher than the criteria set in the study namely 12 cm for edge lines and centre lines.

However, for the marking widths it is unclear how many edge lines meet a width of 15 or 20 cm. Therefore, it is assumed that the *edge line* width for the entire primary road network is currently equal to the lowest value provided namely 15 cm. This value is higher than the recommended width of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 150 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 mcd*m^{-2}*lx^{-1}with 15 cm for centre lines and 15 cm for edge lines
- RW 50 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

3.17.3. Input values for break-even cost-benefit analysis

3.17.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.504.928,00	2.744.900,10
Serious injury	269.149,00	294.933,47
Slight injury	6.031,00	6.608,77
The average harmonised inflation of The Netherlands in 2022: 9.58%		
Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.17.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.17.4. Break-even cost-benefit analysis results

- **Motorways: R_L 150 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for R_L 150 mcd*m^{-2}*lx^{-1}.

- **Motorways: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 1.521.943,20	€ 1.044.565,50	€ 1.834.830,00
20 cm edge line	€ 10.456.444,80	€ 7.176.642,00	€ 12.606.120,00
Total	€ 11.978.388,00	€ 8.221.207,50	€ 14.440.950,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.744.900,10	€ 294.933,47	€ 6.608,77
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	4	3	5
Severely injured	41	28	49
Slightly injured	1812	1244	2185
Average break-even point: cost/benefits			
Fatally injured	4 fatalities		
Severely injured	39 severely injured		
Slightly injured	1.747 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 41 seriously injured **or** 1812 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 3 fatally injured **or** 28 seriously injured **or** 1244 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 49 seriously injured **or** 2185 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 4 fatally injured **or** 39 seriously injured **or** 1.747 slightly injured road users over a 4-year period.

- **Motorways: R$_L$ 300/RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 3.275.654,40	€ 1.848.993,60	€ 2.221.110,00	€ 2.916.414,00	€ 2.575.200,00
20 cm edge line	€ 22.505.241,60	€ 12.703.430,40	€ 15.260.040,00	€ 20.037.096,00	€ 17.692.800,00
Total	€ 25.780.896,00	€ 14.552.424,00	€ 17.481.150,00	€ 22.953.510,00	€ 20.268.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.744.900,10	€ 294.933,47	€ 6.608,77		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	9	5	6	8	7
Severely injured	87	49	59	78	69
Slightly injured	3901	2202	2645	3473	3067
Average break-even point: cost/benefits					
Fatally injured	7 fatalities				
Severely injured	69 severely injured				
Slightly injured	3.058 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 9 fatally injured **or** 87 seriously injured **or** 3901 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 49 seriously injured **or** 2202 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 6 fatally injured **or** 59 seriously injured **or** 2645 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 78 seriously injured **or** 3473 slightly injured road users over a 4-year period.

  In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 7 fatally injured **or** 69 seriously injured **or** 3067 slightly injured road users over a 4-year period

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 7 fatally injured **or** 69 seriously injured **or** 3.058 slightly injured road users over a 4-year period.

- **Primary roads: R$_L$ 150 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 15 cm for edge lines**

The measure cannot be calculated as the supplier did not provide unit costs and service life information for RL 150 mcd*m^{-2}*lx^{-1}.

- **Primary roads: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm edge + centre line	€ 7.491.988,80	€ 5.142.027,00	€ 9.032.220,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.744.900,10	€ 294.933,47	€ 6.608,77
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	3	2	3
Severely injured	25	17	31
Slightly injured	1134	778	1367
Average break-even point: cost/benefits			
Fatally injured	3 fatalities		
Severely injured	24 severely injured		
Slightly injured	1.093 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 25 seriously injured **or** 1134 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 2 fatally injured **or** 17 seriously injured **or** 778 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 31 seriously injured **or** 1367 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 3 fatally injured **or** 24 seriously injured **or** 1.093 slightly injured road users over a 4-year period.

- **Primary roads: RW 50/Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 15 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm edge + centre line	€ 16.124.889,60	€ 9.101.942,40	€ 10.933.740,00	€ 14.356.476,00	€ 12.676.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.744.900,10	€ 294.933,47	€ 6.608,77		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	6	3	4	5	5
Severely injured	55	31	37	49	43
Slightly injured	2440	1377	1654	2172	1918
Average break-even point: cost/benefits					
Fatally injured	5 fatalities				
Severely injured	43 severely injured				
Slightly injured	1.912 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 6 fatally injured **or** 55 seriously injured **or** 2440 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 31 seriously injured **or** 1377 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 4 fatally injured **or** 37 seriously injured **or** 1654 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 49 seriously injured **or** 2172 slightly injured road users over a 4-year period.
- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 5 fatally injured **or** 43 seriously injured **or** 1918 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 5 fatally injured **or** 43 seriously injured **or** 1.912 slightly injured road users over a 4-year period.

3.18. Norway

3.18.1. Current situation

3.18.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	4000	500	4500
Primary road	8000	4000	12000
Source: WP1 survey			

3.18.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	15
Primary road	10/15	10/15
Source: WP1 survey		

3.18.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.18.2. Road marking measures to be calculated

Norwegian ***motorways*** already meet the visibility criteria for R_L (150), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200/300 and Qd 160 $mcd*m^{-2}*lx^{-1}$. Furthermore, the marking widths on the motorway network of 15 cm for centre lines and 30 cm for edge lines already meet or are higher than the criteria set in the study namely 15/20 cm for edge lines and 15 cm for centre lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines

Norwegian ***primary roads*** already meet the visibility criteria for R_L (150), RW (50) and Qd (130) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criteria of R_L 200 and Qd 160 $mcd*m^{-2}*lx^{-1}$. However, for the marking widths it is unclear how many edge and centre lines meet a width of 10 or 15 cm. Therefore, it is assumed that the *edge and centre line* width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. This value is lower than the recommended width of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines

3.18.3. Input values for break-even cost-benefit analysis

3.18.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.690.394,00	2.872.802,71
Serious injury	845.812,00	903.158,05
Slight injury	52.970,00	56.561,37
The average harmonised inflation of Europe in 2022: 6.78%* *Note: European average used since there is no specific HICP value available for Norway Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.18.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
30 cm	€ 1.418,40	€ 973,50	€ 1.710,00

3.18.4. Break-even cost-benefit analysis results

- **Motorways: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 354.600,00	€ 243.375,00	€ 427.500,00
30 cm edge line	€ 5.673.600,00	€ 3.894.000,00	€ 6.840.000,00
Total	€ 6.028.200,00	€ 4.137.375,00	€ 7.267.500,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.872.802,71	€ 903.158,05	€ 56.561,37
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2	1	3
Severely injured	7	5	8
Slightly injured	107	73	128
Average break-even point: cost/benefits			
Fatally injured	2 fatalities		
Severely injured	6 severely injured		
Slightly injured	103 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 7 seriously injured **or** 107 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 1 fatally injured **or** 5 seriously injured **or** 73 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 8 seriously injured **or** 128 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 6 seriously injured **or** 103 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 763.200,00	€ 430.800,00	€ 517.500,00	€ 679.500,00	€ 600.000,00
30 cm edge line	€ 12.211.200,00	€ 6.892.800,00	€ 8.280.000,00	€ 10.872.000,00	€ 9.600.000,00
Total	€ 12.974.400,00	€ 7.323.600,00	€ 8.797.500,00	€ 11.551.500,00	€ 10.200.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.872.802,71	€ 903.158,05	€ 56.561,37		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	5	3	3	4	4
Severely injured	14	8	10	13	11
Slightly injured	229	129	156	204	180
Average break-even point: cost/benefits					
Fatally injured	4 fatalities				
Severely injured	11 severely injured				
Slightly injured	180 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 14 seriously injured **or** 229 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 8 seriously injured **or** 129 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 10 seriously injured **or** 156 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 13 seriously injured **or** 204 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 4 fatally injured **or** 11 seriously injured **or** 180 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 4 fatally injured **or** 11 seriously injured **or** 180 slightly injured road users over a 4-year period.

- **Primary roads: R_L 200 ($mcd*m^{-2}*lx^{-1}$) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm edge + centre lines	€ 6.808.320,00	€ 4.672.800,00	€ 8.208.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.872.802,71	€ 903.158,05	€ 56.561,37
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	2	2	3
Severely injured	8	5	9
Slightly injured	120	83	145
Average break-even point: cost/benefits			
Fatally injured	2 fatalities		
Severely injured	7 severely injured		
Slightly injured	116 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 8 seriously injured **or** 120 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 2 fatally injured **or** 5 seriously injured **or** 83 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 9 seriously injured **or** 145 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 2 fatally injured **or** 7 seriously injured **or** 116 slightly injured road users over a 4-year period.

- **Primary roads: Qd 160 (mcd*m^{-2}*lx^{-1}) with 12 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm edge + centre lines	€ 14.653.440,00	€ 8.271.360,00	€ 9.936.000,00	€ 13.046.400,00	€ 11.520.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.872.802,71	€ 903.158,05	€ 56.561,37		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	5	3	3	5	4
Severely injured	16	9	11	14	13
Slightly injured	259	146	176	231	204
Average break-even point: cost/benefits					
Fatally injured	4 fatalities				
Severely injured	13 severely injured				
Slightly injured	203 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 16 seriously injured **or** 259 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 3 fatally injured **or** 9 seriously injured **or** 146 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 11 seriously injured **or** 176 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 14 seriously injured **or** 231 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 4 fatally injured **or** 13 seriously injured **or** 204 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 4 fatally injured **or** 13 seriously injured **or** 203 slightly injured road users over a 4-year period.

3.19. Poland

3.19.1. Current situation

3.19.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.19.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	24	12/24
Primary road	24	12/24
Source: WP1 survey		

3.19.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	250	250
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	130/160	130/160
Source: WP1 survey		

3.19.2. Road marking measures to be calculated

Polish ***motorways*** already meet the visibility criteria for R_L (250), RW (50) and Qd (130/160) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criterion of R_L 300 $mcd*m^{-2}*lx^{-1}$. However, for Qd it is unclear how many motorways meet 130 or 160 $mcd*m^{-2}*lx^{-1}$. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 $mcd*m^{-2}*lx^{-1}$ for the entire motorway network.

Furthermore, for the marking widths it is unclear how many centre lines meet a width of 12 or 24 cm. Therefore, it is assumed that the *centre line* width for the entire motorway network is currently equal to the lowest value provided namely 12 cm. As a result, the marking width of centre lines on the motorway network does not meet the criterion set in the study namely 15 cm. In addition, the current edge line marking width of 24 cm on motorways is higher than the criterion set in the study namely 15/20 cm for edge lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 24 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 24 cm for edge lines
- Qd 130 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 24 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 24 cm for edge lines

Polish ***primary roads*** already meet the visibility criteria for R_L (250), RW (50) and Qd (130/160) mcd*m^{-2}*lx^{-1}. However, for Qd it is unclear how many motorways meet 130 or 160 mcd*m^{-2}*lx^{-1}. Therefore, it is assumed that Qd is currently equal to the lowest value of 130 mcd*m^{-2}*lx^{-1} for the entire motorway network.

Furthermore, the marking widths on the primary road network of 12/24 cm for centre lines and 24 cm for edge lines already meet or are higher than the criteria set in the study namely 12 cm edge and lines. However, for the marking widths it is unclear how many centre lines meet a width of 12 or 24 cm. Therefore, it is assumed that the *centre line* width for the entire primary road network is currently equal to the lowest value provided namely 12 cm. This value is equal to the recommended width of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measure:

- Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 24 cm for edge lines

3.19.3. Input values for break-even cost-benefit analysis

3.19.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	814.504,00	897.827,76
Serious injury	975.074,00	1.074.824,07
Slight injury	11.536,00	12.716,13
The average harmonised inflation of Poland in 2022: 10.23% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.19.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
24 cm	€ 2.442,24	€ 1.378,56	€ 1.656,00	€ 2.174,40	€ 1.920,00

3.19.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads.

3.20. Portugal

3.20.1. Current situation

3.20.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	11940	7110	19050
Primary road	No data delivered		
Source: WP1 survey			

3.20.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	15
Primary road	15	12
Source: WP1 survey		

3.20.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	200	200
Night-time: wet (RW)	Not requested	50
Day-time: dry (Qd)	Not requested	160
Source: WP1 survey		

3.20.2. Road marking measures to be calculated

Portuguese ***motorways*** already meet the visibility criterion for R_L (200) $mcd*m^{-2}*lx^{-1}$ but do not meet the common visibility criterion of R_L 300 $mcd*m^{-2}*lx^{-1}$. Visibility criteria for Qd and RW are not defined. The edge and centre line markings meet the recommended width of 15 cm for centre lines and 20 cm for edge lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 100 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 130 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines

The road markings on ***primary roads*** in Portugal already meet the visibility and width levels recommended by the study or have higher width levels in place. As a result, there is no need to calculate a break-even cost-benefit analysis for primary roads.

3.20.3. Input values for break-even cost-benefit analysis

3.20.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	838.109,00	886.300,27
Serious injury	136.365,00	144.205,99
Slight injury	35.391,00	37.425,98
The average harmonised inflation of Portugal in 2022: 5.75% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.20.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

3.20.4. Break-even cost-benefit analysis results

- **Motorways: R_L 300/RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 20 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 10.852.704,00	€ 6.125.976,00	€ 7.358.850,00	€ 9.662.490,00	€ 8.532.000,00
20 cm edge line	€ 24.300.288,00	€ 13.716.672,00	€ 16.477.200,00	€ 21.635.280,00	€ 19.104.000,00
Total	€ 35.152.992,00	€ 19.842.648,00	€ 23.836.050,00	€ 31.297.770,00	€ 27.636.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 886.300,27	€ 144.205,99	€ 37.425,98		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	40	22	27	35	31
Severely injured	244	138	165	217	192
Slightly injured	939	530	637	836	738
Average break-even point: cost/benefits					
Fatally injured	31 fatalities				
Severely injured	191 severely injured				
Slightly injured	736 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 40 fatally injured **or** 244 seriously injured **or** 939 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 22 fatally injured **or** 138 seriously injured **or** 530 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 27 fatally injured **or** 165 seriously injured **or** 637 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 35 fatally injured **or** 217 seriously injured **or** 836 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 31 fatally injured **or** 192 seriously injured **or** 738 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 31 fatally injured **or** 191 seriously injured **or** 736 slightly injured road users over a 4-year period.

- **Motorways: RW 35 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 $mcd*m^{-2}*lx^{-1}$. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 $mcd*m^{-2}*lx^{-1}$. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 $mcd*m^{-2}*lx^{-1}$ differs.

- **Motorways: Qd 100 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 100 $mcd*m^{-2}*lx^{-1}$.

- **Motorways: Qd 130 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 20 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for Qd 130 $mcd*m^{-2}*lx^{-1}$.

3.21. Romania

3.21.1. Current situation

3.21.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	3840	634	4474
Primary road	35480	10644	46124
Source: WP1 survey			

3.21.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	15
Primary road	15	15
Source: WP1 survey		

3.21.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	75	75
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.21.2. Road marking measures to be calculated

The road markings on motorways and primary roads in Romania already meet the visibility and width levels recommended by the study or have higher visibility and width levels in place. As a result, there is no need to calculate a break-even cost-benefit analysis.

3.22. Slovakia

3.22.1. Current situation

3.22.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	2100	499	2599
Primary road	1082	268	1350
Source: WP1 survey			

3.22.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	25	12.5
Primary road	25	12.5
Source: WP1 survey		

3.22.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	35/50	35/50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.22.2. Road marking measures to be calculated

Motorways in Slovakia already meet the visibility criteria for R_L (300), RW (35/50) and Qd (160) $mcd*m^{-2}*lx^{-1}$. However, for RW it is unclear how many motorways meet 35 or 50 $mcd*m^{-2}*lx^{-1}$. Therefore, it is assumed that RW is currently equal to the lowest value of 35 for the entire motorway network.

The current marking width of edge lines on motorways of 25 cm is higher than the recommended values of 15/20 cm. However, the current marking width of centre lines on motorways of 12.5 cm is lower than the recommended value of 15 cm.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 25 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 25 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 25 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 25 cm for edge lines

Primary roads in Slovakia already meet the visibility criteria for R_L (300), RW (35/50) and Qd (160) $mcd*m^{-2}*lx^{-1}$. However, for RW it is unclear how many primary roads meet 35 or 50 $mcd*m^{-2}*lx^{-1}$. Therefore, it is assumed that RW is currently equal to the lowest value of 35 $mcd*m^{-2}*lx^{-1}$ for the entire primary road network.

The current marking width of edge lines on primary roads of 25 cm is higher than the recommended values of 12 cm. Additionally, the current marking width of centre lines on primary roads of 12.5 cm is higher than the recommended value of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measure:

- RW 50 mcd*m^{-2}*lx^{-1} with 12.5 cm for centre lines and 25 cm for edge lines

3.22.3. Input values for break-even cost-benefit analysis

3.22.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	652.238,00	715.048,52
Serious injury	141.504,00	155.130,84
Slight injury	20.767,00	22.766,86
The average harmonised inflation of Slovakia in 2022: 9.63% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.22.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / RL 300 / Qd 160					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12,5 cm	€ 1.272,00	€ 718,00	€ 862,50	€ 1.132,50	€ 1.000,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
25 cm	€ 2.544,00	€ 1.436,00	€ 1.725,00	€ 2.265,00	€ 2.000,00

3.22.4. Break-even cost-benefit analysis results

- **Motorways: RL 300/RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 25 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 761.673,60	€ 429.938,40	€ 516.465,00	€ 678.141,00	€ 598.800,00
25 cm edge line	€ 5.342.400,00	€ 3.015.600,00	€ 3.622.500,00	€ 4.756.500,00	€ 4.200.000,00
Total	€ 6.104.073,60	€ 3.445.538,40	€ 4.138.965,00	€ 5.434.641,00	€ 4.798.800,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 715.048,52	€ 155.130,84	€ 22.766,86		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	9	5	6	8	7
Severely injured	39	22	27	35	31
Slightly injured	268	151	182	239	211
Average break-even point: cost/benefits					
Fatally injured	7 fatalities				
Severely injured	31 severely injured				
Slightly injured	210 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 9 fatally injured **or** 39 seriously injured **or** 268 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 22 seriously injured **or** 151 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 6 fatally injured **or** 27 seriously injured **or** 182 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 35 seriously injured **or** 239 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 7 fatally injured **or** 31 seriously injured **or** 211 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 7 fatally injured **or** 31 seriously injured **or** 210 slightly injured road users over a 4-year period.

- **Motorways: RW 35 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 25 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50 (mcd*m^{-2}*lx^{-1}) with 12.5 cm for centre lines and 25 cm for edge lines**

Costs	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
12,5 cm centre line	€ 340.896,00	€ 192.424,00	€ 231.150,00	€ 303.510,00	€ 268.000,00
25 cm edge line	€ 2.752.608,00	€ 1.553.752,00	€ 1.866.450,00	€ 2.450.730,00	€ 2.164.000,00
Total	€ 3.093.504,00	€ 1.746.176,00	€ 2.097.600,00	€ 2.754.240,00	€ 2.432.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 715.048,52	€ 155.130,84	€ 22.766,86		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	4	2	3	4	3
Severely injured	20	11	14	18	16
Slightly injured	136	77	92	121	107
Average break-even point: cost/benefits					
Fatally injured	3 fatalities				
Severely injured	16 severely injured				
Slightly injured	107 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 20 seriously injured **or** 136 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 2 fatally injured **or** 11 seriously injured **or** 77 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 14 seriously injured **or** 92 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 4 fatally injured **or** 18 seriously injured **or** 121 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 3 fatally injured **or** 16 seriously injured **or** 107 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 3 fatally injured **or** 16 seriously injured **or** 107 slightly injured road users over a 4-year period.

3.23. Slovenia

3.23.1. Current situation

3.23.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	2240	1120	3360
Primary road	86	43	129
Source: WP1 survey			

3.23.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	20	15
Primary road	12/15	12/15
Source: WP1 survey		

3.23.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	300	300
Night-time: wet (RW)	50	50
Day-time: dry (Qd)	160	160
Source: WP1 survey		

3.23.2. Road marking measures to be calculated

The road markings on motorways and primary roads in Slovenia already meet the visibility and width levels recommended by the study or have higher width levels in place. As a result, there is no need to calculate a break-even cost-benefit analysis.

3.24. Spain

3.24.1. Current situation

3.24.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	No data delivered		
Primary road	No data delivered		
Source: WP1 survey			

3.24.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	15	15
Primary road	15	15
Source: WP1 survey		

3.24.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	No data delivered	No data delivered
Night-time: wet (RW)	No data delivered	No data delivered
Day-time: dry (Qd)	No data delivered	No data delivered
Source: WP1 survey		

3.24.2. Road marking measures to be calculated

There is no data about road marking visibility on ***motorways*** available. The marking widths for edge and centre lines on motorways meet the recommended criteria of 15 cm but the not the recommended criterion of 20 cm for edge lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 150 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- Qd 100 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines
- Qd 130 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 20 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$with 15 cm for centre lines and 20 cm for edge lines

There is no data about road marking visibility on ***primary roads*** available. The marking widths for edge and centre lines on primary roads are higher than recommended criteria of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 150 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 15 cm for edge lines

- Qd 100 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines
- Qd 160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

3.24.3. Input values for break-even cost-benefit analysis

3.24.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	1.592.359,00	1.720.862,37
Serious injury	254.777,00	275.337,50
Slight injury	6.938,00	7.497,90
The average harmonised inflation of Spain in 2022: 8.07% Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)		

3.24.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
20 cm	€ 2.035,20	€ 1.148,80	€ 1.380,00	€ 1.812,00	€ 1.600,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm	€ 709,20	€ 486,75	€ 855,00
20 cm	€ 945,60	€ 649,00	€ 1.140,00

3.24.4. Break-even cost-benefit analysis results

Currently, the break-even cost-benefit analysis cannot be calculated due to missing data about the length of edge and centre lines on motorways and primary roads.

3.25. Sweden

3.25.1. Current situation

3.25.1.1. Length of road markings

Road type	Edge line (km)	Centre line (km)	Total (km)
Motorway	8488	4244	12732
Primary road	12602	6301	18903
Source: WP1 survey			

3.25.1.2. Road marking width

Road type	Edge line (cm)	Centre line (cm)
Motorway	30	15
Primary road	10/15	15
Note: Road markings differ depending on AADT, speed and width of the road.		
Source: WP1 survey		

3.25.1.3. Road marking visibility

	Motorway ($mcd*m^{-2}*lx^{-1}$)	Primary road ($mcd*m^{-2}*lx^{-1}$)
Night-time: dry (R_L)	150	150
Night-time: wet (RW)	35	35
Day-time: dry (Qd)	130	130
Source: WP1 survey		

3.25.2. Road marking measures to be calculated

Swedish ***motorways*** already meet the visibility criteria for R_L (150), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criteria of R_L 200/300, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. The marking widths for edge and centre lines on motorways meet or are higher than the recommended criteria of 15 cm for centre lines and 15/20 cm for edge lines.

Therefore, the break-even cost-benefit analysis for motorways is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- R_L 300 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 30 cm for edge lines

Swedish ***primary roads*** already meet the visibility criteria for R_L (150), RW (35) and Qd (130) $mcd*m^{-2}*lx^{-1}$but do not meet the common visibility criteria of R_L 200, RW 50 and Qd 160 $mcd*m^{-2}*lx^{-1}$. The marking width of centre lines on primary roads meet are higher than the recommended criterion of 12 cm for centre lines. However, for the marking widths it is unclear how many edge lines meet a width of 10 or 15 cm. Therefore, it is assumed that the edge line width for the entire primary road network is currently equal to the lowest value provided namely 10 cm. This value is lower than the recommended width of 12 cm.

Therefore, the break-even cost-benefit analysis for primary roads is calculated for the following measures:

- R_L 200 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 12 cm for edge lines
- RW 35 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 12 cm for edge lines
- RW 50 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 12 cm for edge lines
- Qd 160 $mcd*m^{-2}*lx^{-1}$ with 15 cm for centre lines and 12 cm for edge lines

3.25.3. Input values for break-even cost-benefit analysis

3.25.3.1. Unit cost per casualty

Casualty	Unit cost in Euro (2015)	Unit cost in Euro (2022)
Fatal injury	2.160.235,00	2.284.664,54
Serious injury	399.728,00	422.752,33
Slight injury	19.561,00	20.687,71

The average harmonised inflation of Sweden in 2022: 5.76%

Source: Eurostat (2022) and Inflation.eu (2022), Unit cost (2015) from Safetycube D3.2 (2018)

3.25.3.2. Implementation costs for a service life of 4 years (Cost per km lane width)

RW 50 / R_L 300 / Qd 160 mcd*m^{-2}*lx^{-1}					
Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
12 cm	€ 1.221,12	€ 689,28	€ 828,00	€ 1.087,20	€ 960,00
15 cm	€ 1.526,40	€ 861,60	€ 1.035,00	€ 1.359,00	€ 1.200,00
30 cm	€ 3.052,80	€ 1.723,20	€ 2.070,00	€ 2.718,00	€ 2.400,00

R_L 200 / Qd 160 mcd*m^{-2}*lx^{-1}			
Material	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
12 cm	€ 567,36	€ 389,40	€ 684,00
15 cm	€ 709,20	€ 486,75	€ 855,00
30 cm	€ 1.418,40	€ 973,50	€ 1.710,00

3.25.4. Break-even cost-benefit analysis results

- **Motorways: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 3.009.844,80	€ 2.065.767,00	€ 3.628.620,00
30 cm edge line	€ 12.039.379,20	€ 8.263.068,00	€ 14.514.480,00
Total	€ 15.049.224,00	€ 10.328.835,00	€ 18.143.100,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.284.664,54	€ 422.752,33	€ 20.687,71
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	7	5	8
Severely injured	36	24	43
Slightly injured	727	499	877
Average break-even point: cost/benefits			
Fatally injured	6 fatalities		
Severely injured	34 severely injured		
Slightly injured	701 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 7 fatally injured **or** 36 seriously injured **or** 727 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 5 fatally injured **or** 24 seriously injured **or** 499 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 43 seriously injured **or** 877 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 6 fatally injured **or** 34 seriously injured **or** 701 slightly injured road users over a 4-year period.

- **Motorways: R_L 300/RW 50/Qd 160 ($mcd*m^{-2}*lx^{-1}$) with 15 cm for centre lines and 30 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 6.478.041,60	€ 3.656.630,40	€ 4.392.540,00	€ 5.767.596,00	€ 5.092.800,00
30 cm edge line	€ 25.912.166,40	€ 14.626.521,60	€ 17.570.160,00	€ 23.070.384,00	€ 20.371.200,00
Total	€ 32.390.208,00	€ 18.283.152,00	€ 21.962.700,00	€ 28.837.980,00	€ 25.464.000,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.284.664,54	€ 422.752,33	€ 20.687,71		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	14	8	10	13	11
Severely injured	77	43	52	68	60
Slightly injured	1.566	884	1.062	1.394	1.231
Average break-even point: cost/benefits					
Fatally injured	11 fatalities				
Severely injured	60 severely injured				
Slightly injured	1227 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 14 fatally injured **or** 77 seriously injured **or** 1.566 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 8 fatally injured **or** 43 seriously injured **or** 884 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 10 fatally injured **or** 52 seriously injured **or** 1.062 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 13 fatally injured **or** 68 seriously injured **or** 1.394 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 11 fatally injured **or** 60 seriously injured **or** 1.231 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 11 fatally injured **or** 60 seriously injured **or** 1227 slightly injured road users over a 4-year period.

- **Primary roads: R_L 200 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	Thermoplastic
	Flatline	Flatline	Flatline
15 cm centre line	€ 4.468.669,20	€ 3.067.011,75	€ 5.387.355,00
12 cm edge line	€ 7.149.870,72	€ 4.907.218,80	€ 8.619.768,00
Total	€ 11.618.539,92	€ 7.974.230,55	€ 14.007.123,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**
	€ 2.284.664,54	€ 422.752,33	€ 20.687,71
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**Thermoplastic**
	Flatline	Flatline	Flatline
Fatally injured	5	3	6
Severely injured	27	19	33
Slightly injured	562	385	677
Average break-even point: cost/benefits			
Fatally injured	5 fatalities		
Severely injured	26 severely injured		
Slightly injured	541 slightly injured		

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 5 fatally injured **or** 27 seriously injured **or** 562 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline**) road markings it is required that this road marking measure saves 3 fatally injured **or** 19 seriously injured **or** 385 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 6 fatally injured **or** 33 seriously injured **or** 677 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 5 fatally injured **or** 26 seriously injured **or** 541 slightly injured road users over a 4-year period.

- **Primary roads: RW 35 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 12 cm for edge lines**

  The measure cannot be calculated as the supplier did not provide unit costs and service life information for RW 35 mcd*m^{-2}*lx^{-1}. However, the supplier did mention that there is no initial material cost difference if one wants to achieve RW 35 or RW 50 mcd*m^{-2}*lx^{-1}. Both visibility levels require the same amount of material as there is only a slight difference in the number of drop-on beads that is used. But this insignificant from a cost point of view. However, the expected service life of RW 35 and RW 50 mcd*m^{-2}*lx^{-1} differs.

- **Primary roads: RW 50/Qd 160 (mcd*m^{-2}*lx^{-1}) with 15 cm for centre lines and 12 cm for edge lines**

Costs	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
	Flatline	Flatline	Structure	Flatline	Structure
15 cm centre line	€ 9.617.846,40	€ 5.428.941,60	€ 6.521.535,00	€ 8.563.059,00	€ 7.561.200,00
12 cm edge line	€ 15.388.554,24	€ 8.686.306,56	€ 10.434.456,00	€ 13.700.894,40	€ 12.097.920,00
Total	€ 25.006.400,64	€ 14.115.248,16	€ 16.955.991,00	€ 22.263.953,40	€ 19.659.120,00
Benefits	**Fatally injured**	**Seriously injured**	**Slightly injured**		
	€ 2.284.664,54	€ 422.752,33	€ 20.687,71		
Break-even point: cost/benefits	**Paint**	**Coldspray Plastic**	**ColdPlastic**	**Thermoplastic**	**Thermoplastic**
	Flatline	Flatline	Structure	Flatline	Structure
Fatally injured	11	6	7	10	9
Severely injured	59	33	40	53	47
Slightly injured	1.209	682	820	1.076	950
Average break-even point: cost/benefits					
Fatally injured	9 fatalities				
Severely injured	46 severely injured				
Slightly injured	947 slightly injured				

The results of the break-even cost-benefit analysis indicate the following:

- In order to reach the break-even point for investing in **paint (flatline)** road markings it is required that this road marking measure saves 11 fatally injured **or** 59 seriously injured **or** 1.209 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldspray plastic (flatline)** road markings it is required that this road marking measure saves 6 fatally injured **or** 33 seriously injured **or** 682 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **coldplastic (structure)** road markings it is required that this road marking measure saves 7 fatally injured **or** 40 seriously injured **or** 820 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (flatline)** road markings it is required that this road marking measure saves 10 fatally injured **or** 53 seriously injured **or** 1.076 slightly injured road users over a 4-year period.

- In order to reach the break-even point for investing in **thermoplastic (structure)** road markings it is required that this road marking measure saves 9 fatally injured **or** 47 seriously injured **or** 950 slightly injured road users over a 4-year period.

Regardless of the chosen road marking material, the average break-even point is reached if the improved road marking saves 9 fatally injured **or** 46 seriously injured **or** 947 slightly injured road users over a 4-year period.

4. CONCLUSIONS

4.1. General findings

The general findings that are presented here are based on the benefit-cost ratio for nine Member States that currently apply lower threshold values than the common minimal values for road marking width and visibility evaluated in this study. The other 15 Member States currently have higher visibility levels (but lower width levels) or higher width levels (but lower visibility levels) than the common minimal values in place. This makes it quite complicated to assign the identified effect to reaching the common minimal values for visibility or marking width only as this identified effect can also originate from combining:

- Higher visibility levels (than the common minimum values) with a common minimum level for width
- Higher road marking widths (than the common minimum values) with a common minimum level for visibility

The combination of a common minimal visibility/width level and higher width/visibility than commonly defined makes it quite complicated to conclude which characteristic (the higher width/visibility or common minimal visibility/width level) generates the road safety benefit. Therefore, these results are omitted from this conclusion as they are out of scope for this study.

4.1.1. Motorways

- RL 150, RW 35, Qd 100/130 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15/20 cm for edge lines

  These measures could not be calculated as the supplier did not provide unit costs and service life information for these common visibility and width levels.

- RL 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

  Only 2 Member States, Hungary and Ireland did not yet meet this common minimal value. The break-even point ranges from 1-2 fatalities or 6-7 severely injured to 64-6.707 slightly injured over a 4-year period in Ireland and Hungary. Put differently, For Hungary, the measure should save 1% of the total fatalities or seriously injured occurring in crashes on motorways over a period of 4-years. For slightly injured, the measure should save 2,76 times the current total number of slightly injured occurring in crashes on motorways over a period of 4-years. In other words, if Hungary decides to invest in this measure it takes more than 4-years (the service life of the most expensive marking material) to reach the break-even point if the measure would only result in a reduction in the number of slightly injured.

Member State	Fatalities	Severely injured	Slightly injured
Hungary	2 (1)	7 (1)	6.707 (276)
Ireland	1*	6*	64*

Note: values between () represent the required percentage reduction in the number of all casualties on motorways of a certain severity in a 4-year period in order to reach the break-even point.

* No values available in the CARE database

- RL 200 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

  Five Member States did not yet meet this common minimal value. These Member States and the related break-even point are listed below:

Member State	Fatalities	Severely injured	Slightly injured
Finland	2 (7)	7 (15)	152*
Germany	43 (3)	426 (2)	10.276 (10)
Hungary	2 (1)	9 (1)	8.609 (354)
Netherlands	4 (1)	39 (1)	1747 (100)
Ireland	1*	8*	83*

Note: values between () represent the required percentage reduction in the number of all casualties on motorways of a certain severity in a 4-year period in order to reach the break-even point.

* No values available in the CARE database

The break-even point ranges from 1 fatality or 8 severely injured or 83 slightly injured in Ireland to 43 fatalities or 426 severely injured or 10.726 slightly injured in Germany over a 4-year period. Put differently, the measure should save between 1-7% of the total fatalities or 1-15% of the total seriously injured or 10-100% (or in case of Hungary 3.5 times) the total number of slightly injured occurring in crashes on motorways over a period of 4-years. In other words, if Hungary decides to invest in this measure it takes more than 4-years (the service life of the most expensive marking material) to reach the break-even point if the measure would only result in a reduction in the number of slightly injured.

- RL 300/RW 50/Qd160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 15 cm for edge lines

  Only 2 Member States, Hungary and Ireland did not yet meet this common minimal value. The break-even point ranges from 1-3 fatalities or 10-13 severely injured to 112-11.737 slightly injured over a 4-year period in Ireland and Hungary. Put differently, the measure should save 2 % of the total fatalities or seriously injured occurring in crashes on motorways over a period of 4-years. For slightly injured, the measure should save 4,83 times the current total number of slightly injured occurring in crashes on motorways over a period of 4-years. In other words, if Hungary decides to invest in this measure it takes more than 4-years (the service life of the most expensive marking material) to reach the break-even point if the measure would only result in a reduction in the number of slightly injured.

Member State	Fatalities	Severely injured	Slightly injured
Hungary	3 (2)	13 (2)	11.737(483)
Ireland	1*	10*	112*

Note: values between () represent the required percentage reduction in the number of all casualties on motorways of a certain severity in a 4-year period in order to reach the break-even point.

* No values available in the CARE database

- RL 300/RW 50/Qd160 mcd*m^{-2}*lx^{-1} with 15 cm for centre lines and 20 cm for edge lines

Seven Member States did not yet meet this common minimal value. These Member States and the related break-even point are listed below:

Member State	Fatalities	Severely injured	Slightly injured
Austria	6 (4)	47 (5)	664 (7)
Finland	3 (11)	12 (25)	266*
Germany	76 (5)	746 (3)	17.983 (18)
Hungary	4 (2)	17 (2)	15.066 (619)
Netherlands	7 (2)	69(2)	3.058 (177)
Portugal	31 (13)	191 (37)	736 (7)
Ireland	2*	13*	145*

Note: values between () represent the required percentage reduction in the number of all casualties on motorways of a certain severity in a 4-year period in order to reach the break-even point.

* No values available in the CARE database

The break-even point ranges from 2 fatalities or 13 severely injured or 145 slightly injured in Ireland to 76 fatalities or 746 severely injured or 17.983 slightly injured in Germany over a 4-year period. Put differently, the measure should save between 2-13% of the total fatalities or 2-37% of the total seriously injured or 7-18% (or in case of: Hungary 6.19 times, Netherlands 1.77 times) the total number of slightly injured occurring in crashes on motorways over a period of 4-years. In other words, if Hungary and the Netherlands decide to invest in this measure it takes more than 4-years (the service life of the most expensive marking material) to reach the break-even point if the measure would only result in a reduction in the number of slightly injured.

4.1.2. Primary roads

- RL 150, RW 35, Qd 100/130 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines

These measures could not be calculated as the supplier did not provide unit costs and service life information for these common visibility and width levels.

- RL 200 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines

Three Member States did not yet meet this common minimal value. These Member States and the related break-even point are listed below:

Member State	Fatalities	Severely injured	Slightly injured
Iceland	2	16	81
Norway	2	7	116
Finland	9	30	695

Note: The required percentage reduction in the number of all casualties on primary roads of a certain severity in a 4-year period in order to reach the break-even point could not be calculated due to missing injury and crash data for primary roads in the CARE database.

The break-even point ranges from 2-9 fatalities or 7-30 severely injured to 81-695 slightly injured over a 4-year period in Iceland, Norway and Finland.

- RW 50/Qd 160 mcd*m^{-2}*lx^{-1} with 12 cm for centre lines and 12 cm for edge lines

  Five Member States did not yet meet this common minimal value. These Member States and the related break-even point are listed below:

Member State	Fatalities	Severely injured	Slightly injured
Croatia	7	55	722
Germany	84	826	19.920
Iceland	4	28	142
Norway	4	13	203
Finland	15	53	1.216

Note: The required percentage reduction in the number of all casualties on primary roads of a certain severity in a 4-year period in order to reach the break-even point could not be calculated due to missing injury and crash data for primary roads in the CARE database.

The break-even point ranges from 4 fatalities or 13 severely injured or 203 slightly injured in Norway to 84 fatalities or 826 severely injured or 19.920 slightly injured in Germany over a 4-year period.

4.2. How to use these results?

These results must be interpreted with caution as they are based on the benefit cost ratio of only nine Member States and the applied method suffers from several severe limitations listed in paragraph 2.6.

The most important limitation is that no crash or injury data related to target crashes is used. The benefit side only consists of the unit cost per fatality, severely and slightly injured persons involved in a crash. Consequently, the effects/benefits of improved road markings are overestimated since we cannot be 100% sure that better markings will have the same effect on all these crashes and injuries. In the current analysis, a 100% effectiveness on all crashes is assumed, i.e., the improved marking reduces the target crashes to zero. This significant overestimation can only be further decreased by doing a detailed benefit calculation based on target crashes and CMFs. CMFs could assist in lowering the overestimation, but there are no reliable CMFs available for the Europe. Therefore, the results of this break-even analysis are an overestimation of the required effectiveness of improved road markings since it assumes that this measure would have an impact on all possible crashes and injuries on motorways and primary roads whereas in reality it is very likely that the assumed effectiveness on the target crashes is not equal to 100% but to a lower percentage.

Secondly, the effect of incremental higher visibility and width levels cannot be considered. This is only possible with Crash modification Factors (CMFs). For this study, it means that the incremental change in visibility and width levels was only considered in the cost side but not in the benefit side without using CMFs. To illustrate, in order to include this incremental change in the benefit side we should know or find a value indicating how many crashes are caused in Europe by bad marking visibility or a too narrow marking width (which is not available). For example, we should know how many crashes can be avoided if we go from a visibility of 100 to 130 to 150 mcd*m^{-2}*lx^{-1} and this incremental change can only be measured by means of CMFs if they are available. For the same reason, the analysis cannot differentiate between the costs and benefits of improved road markings for human drivers or ADAS. This is only possible with the use of CMFs.

Finally, there are large differences in official estimates of road crash costs in European countries. The cost per fatality ranges from €0.7 million to €3.2 million. The costs per serious injury range from €30.000 to €1 million, and the costs per slight injury from €316 to €75.000. The differences are largely explained by differences in methodologies, in particular whether or not a willingness to pay method is applied to estimate human costs, differences in costs components that are included, different definitions of serious and slight injuries and differences in reporting rates of crashes and injuries (Wijnen et al., 2017).

Higher unit costs per casualty severely impacts the break-even result. Member States with higher unit costs per casualty will reach the break-even point sooner as they need less time (need to save fewer casualties) to recover the investment. Whereas Member States with lower unit costs per casualty will need to undertake more efforts in order to recover the investment costs within the service life time.

To conclude, given these differences between Member States, the findings cannot be extrapolated to all Member States. Given the assumption that all crashes are affected by the measures, leading to a significant overestimation of the benefits, it is strongly advised to treat these results with caution and to bear in mind the possible bias in these results. Therefore, the results of this analysis only serve as a first indication of the expected costs and benefits of the minimum common visibility and width levels for road markings on motorways and primary roads in Europe.

It is strongly advised to research these effects further in a cost-benefit analysis when CMFs become available that reflect the incremental change in visibility and width levels. This is the only approach to capture the effect of incremental higher road marking visibility and width levels.

For some common specifications, the results indicate a positive direction related to this introduction however the value of the effect is highly disputable. However, it is expected that introducing common specifications for road markings and signs will be inevitable in the future when autonomous vehicles will become more common.

REFERENCES

- Ben-Bassat, T. (2019). Are ergonomically designed road signs more easily learned? *Applied Ergonomics*, *78*, 137–147. https://doi.org/10.1016/j.apergo.2019.02.009
- Ben-Bassat, T., & Shinar, D. (2006). Ergonomic guidelines for traffic sign design increase sign comprehension. *Human Factors*, *48*(1), 182–195. https://doi.org/10.1518/001872006776412298
- Eurostat. (2022). *HICP - annual data (average index and rate of change)*. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=prc_hicp_aind
- Inflation.eu. (2022). *Harmonised inflation Belgium 2022 – HICP inflation Belgium 2022*. https://www.inflation.eu/en/inflation-rates/belgium/historic-inflation/hicp-inflation-belgium-2022.aspx
- Ng, A. W. Y., & Chan, A. H. S. (2007). The guessability of traffic signs: Effects of prospective-user factors and sign design features. *Accident Analysis & Prevention*, *39*(6), 1245–1257. https://doi.org/10.1016/j.aap.2007.03.018
- Shinar, D., Dewar, R., Summala, H., & Zakowska, L. (2003). Traffic sign symbol comprehension: A cross-cultural study. *Ergonomics*, *46*(15), 1549–1565. https://doi.org/10.1080/0014013032000121615
- Wijnen, W., Weijermans, W., Vanden Berghe, W., Schoeters, A., Bauer, R., Carnis, L., Elvik, R., Theofilatos, A., Filtness, A., Reed, S., Perez, C., & Martsensen, H. (2017). *Crash cost estimates for European countries* [Deliverable 3.2 of the H2020 project SafetyCube.].
- Yuan, L., Ma, Y.-F., Lei, Z.-Y., & Xu, P. (2014). Driver's Comprehension and Improvement of Warning Signs. *Advances in Mechanical Engineering*, *6*(0), Article 0. https://cyberleninka.org/article/n/1405040

ANNEX

ANNEX 1.1: OVERVIEW OF COSTS TO IMPLEMENT ROAD MARKINGS OF CERTAIN VISIBILITY LEVELS AND WIDTH

Initial performance requirements for Type II markings: RW 50 / RL 300 / Qd 160

Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
Type of Lane	**Flatline**	**Flatline**	**Structure**	**Flatline**	**Structure**
Film thickness in mm	0,6	0,4	-	3,0	-
Density	1,57	1,58	1,84	2,00	2,00
Consumption kg / m²	0,9	0,6	2,6	6,0	4,0
Price € / kg	2,00	3,50	2,50	1,40	1,40
Drop-On Bead consumption kg / m²	0,6	0,6	0,5	0,6	0,5
Price € / kg Bead	1,10	1,10	0,80	1,10	0,80
Total Material Costs / m²	**2,54 €**	**2,87 €**	**6,90 €**	**9,06 €**	**6,00 €**
Cost per km lane width					
10 cm	254 €	287 €	690 €	906 €	600 €
12 cm	305 €	345 €	828 €	1.087 €	720 €
12,5 cm	318 €	359 €	863 €	1.133 €	750 €
15 cm	382 €	431 €	1.035 €	1.359 €	900 €
18 cm	458 €	517 €	1.242 €	1.631 €	1.080 €
20 cm	509 €	574 €	1.380 €	1.812 €	1.200 €
22,5 cm	572 €	646 €	1.553 €	2.039 €	1.350 €
24 cm	611 €	689 €	1.656 €	2.174 €	1.440 €
25 cm	636 €	718 €	1.725 €	2.265 €	1.500 €
30 cm	763 €	862 €	2.070 €	2.718 €	1.800 €
Min Lifetime in years	0,5	1,0	2,0	2,0	2,0
Expectable Lifetime in years	1,0	2,0	4,0	4,0	3,0

Service life for 4 years (calculation based on expectable life time in years and converted to the costs per km lane width over a period of 4 years):

Material	Paint	Coldspray Plastic	ColdPlastic	Thermoplastic	Thermoplastic
Type	**Flatline**	**Flatline**	**Structure**	**Flatline**	**Structure**
10 cm	1018 €	574 €	690 €	906 €	800 €
12 cm	1221 €	689 €	828 €	1087 €	960 €
12,5 cm	1272 €	718 €	863 €	1133 €	1000 €
15 cm	1526 €	862 €	1035 €	1359 €	1200 €
18 cm	1832 €	1034 €	1242 €	1631 €	1440 €
20 cm	2035 €	1149 €	1380 €	1812 €	1600 €
22,5 cm	2290 €	1292 €	1553 €	2039 €	1800 €
24 cm	2442	1379 €	1656 €	2174 €	1920 €
25 cm	2544 €	1436 €	1725 €	2265 €	2000 €
30 cm	3053 €	1723 €	2070 €	2718 €	2400 €

Initial performance requirements for Type I (low standard) markings: RL200 / Qd160

Material	Paint	Coldspray Plastic	Thermoplastic
Type of Lane	Flatline	Flatline	Flatline
Film thickness in mm	0,3	0,25	3
Density of Material	1,57	1,58	2,00
Consumption kg / m²	0,47	0,40	6,00
Price € / kg	2,00	3,50	0,90
Drop-On Bead consumption kg / m²	0,4	0,4	0,5
Price € / kg Bead	0,60	0,60	0,60
Total Material Costs / m²	**1,18 €**	**1,62 €**	**5,70 €**
Cost per km lane width			
10 cm	118 €	162 €	570 €
12 cm	142 €	195 €	684 €
12,5 cm	148 €	203 €	713 €
15 cm	177 €	243 €	855 €
18 cm	213 €	292 €	1.026 €
20 cm	236 €	325 €	1.140 €
22,5 cm	266 €	365 €	1.283 €
24 cm	284 €	389 €	1.368 €
25 cm	296 €	406 €	1.425 €
30 cm	355 €	487 €	1.710 €
Min Lifetime in years	0,5	1,0	2,0
Expectable Lifetime in years	1,0	2,0	4,0

Service life for 4 years (calculation based on expectable life time in years and converted to the costs per km lane width over a period of 4 years):

Material	Paint	Coldspray Plastic	Thermoplastic
Type	**Flatline**	**Flatline**	**Flatline**
10 cm	473 €	325 €	570 €
12 cm	567 €	389 €	684 €
12,5 cm	591 €	406 €	713 €
15 cm	709 €	487 €	855 €
18 cm	851 €	584 €	1.026 €
20 cm	946 €	649 €	1.140 €
22,5 cm	1.064 €	730 €	1.283 €
24 cm	1.135 €	779 €	1.368 €
25 cm	1.182 €	811 €	1.425 €
30 cm	1.418 €	974 €	1.710 €

ANNEX 1.2: LENGTH IN KM OF EDGE LINES AND CENTRE LINES ON MOTORWAYS AND PRIMARY ROADS IN EACH MEMBER STATE

Country	Motorways		Primary roads		Remark
	Centre line	Edge line	Centre line	Edge line	
Austria	5.145	9.000	-	-	No definition of primary roads
Belgium	400	1.700	-	-	Only for Wallonia (Total km motorway = 1763 Km primary road = 13229)
Bulgaria	1600	3200	3000	6000	
Croatia	4.319	8.619	7.175	10.763	The data for the motorways is for one direction.
Cyprus	-	-	-		
Estonia	-	-	-		No roads classified as motorways
Finland	1.900	3.700	13.000	26.000	
France	42.200	46.600	13.500	26.500	
Germany	21.667	43.333	36.667	73.333	
Hungary	881	5.036	2.612	15.674	
Iceland	-	-	4.490	6.620	No roads classified as motorways
Ireland	250	1.888	4.000	4.298	
Italy	-	-	-		No data delivered
Latvia	-	-	-		No roads classified as motorways
Lithuania	860	1.720	1.446	2.892	
Luxembourg	330	1.000	-	-	No data delivered
Norway	500	4.000	4.000	8.000	
Poland					No data delivered
Portugal	7.110	11.940	-	-	
Romania	634	3.840	10.644	35.480	
Slovakia	499	2.100	268	1.082	
Slovenia	1.120	2.240	43	86	
Spain	-	-	-	-	No data delivered
Sweden	4.244	8.488	6.301	12.602	
The Netherlands					longitudinal markings on both types of roads is totalized: 26.796km (km motorway = 2756; Km primary road = 2629)

ANNEX 1.3: CURRENT SITUATION REGARDING ROAD MARKING WIDTH AND VISIBILITY LEVELS ON MOTORWAYS AND PRIMARY ROADS OF EACH MEMBER STATE

Standard widths of longitudinal road markings

	Motorways		Primary roads	
Country	Centre line	Edge line	Centre line	Edge line
Austria	15	20/30[1]	NA	NA
Belgium (Wallonia)	20	30	15	20
Bulgaria	15	25	10	15
Croatia	20	20	12/15	12/15
Cyprus	20	20	10/15	10/15
Estonia	15[2]	20/30[2]	10/15	10/15/20/30
Finland*	10	20	10	10
France**	15	22.5	12/15	18/22.5
Germany***	15	15/30	12	12/25
Hungary	12/15	15/20	12	15
Iceland****	NA	NA	10	10
Ireland	10	15	15	15
Italy	15	25	15[3]	12/25[3]
Latvia	NA	NA	10/15/20	10/15/20
Lithuania	15	30	12	25
Luxembourg	15	22.5	12	12
Norway	15	30	10/15	10/15
Poland	12/24	24	12/24	24
Portugal	15	20	12	15
Romania	15	25	15	15
Slovakia	12.5	25	12.5	25
Slovenia	15	20	12/15	12/15
Spain	15	15	15	15
Sweden*****	15	30	15	10/15
The Netherlands	15	20	15	15/20

NA – Not applicable
1 - 30 cm edge line at exit and entries; 2 – Expressways (2+2 and 2+1 lane roads); 3 – On the suburban and main urban and suburban motorways the module is: 25-15-25, on the suburban secondary and urban traffic and neighborhood the module is: 15-12-15, while on local roads (urban and extra-urban) the form is: 12-10-12.
* Centre line can be 30 cm or 40 cm (or 60 cm) on motorway weaving sections. Edge line can be 30 cm or 40 cm on primary road or motorway weaving sections (and even 60 cm) on motorway weaving sections.
** "Non motorway dual carriageways" - centre line: 15cm, edge line: 22,5 cm;
** "Single carriageways" - centre line: 12 cm, edge line: 18 cm
*** Motorways: left edge line 15 or 30 cm, right edge line or dashed right edge line 30 cm, dashed centre line 15 cm. National Roads: edge lines 12 cm, edge lines to separate hard shoulder/bus stops or dashed right edge line 25 cm, dashed centre marking: 12 cm.
**** On the busiest road outside Reykjavík 20 cm edge and 12 cm centre lines are used.
***** Depending on AADT, speed and width of the road, the road markings differ.

Minimal values of daytime and night-time visibility (for condition of wetness and rain), luminance factor and skid resistance for road markings on motorways

	Motorways									
Country	**Qd – NM**	**Qd - RE**	**R_L – NM**	**R_L - RE**	**RW – NM**	**RW - RE**	**RR – NM**	**RR - RE**	**β**	**SRT**
Austria	100/130[1]	100/130[1]	200	100	35	25	35	25	NR	45
Belgium	160/130[1]	160/130[1]	150	150	25	25	25	25	NR	45
Bulgaria	160	130	300	150	50	35	NR	NR	0.5	55
Croatia	160	100	300	150	50	35	NR	NR	0.4	45
Cyprus	130/100[2]	NR	200/150[2]	NR	35	NR	NR	NR	LF6	45
Estonia*	130	NR	150	NR	35	NR	35	NR	NR	55
Finland	130	130	150	100	NR	NR	NR	NR	0.8	45
France	100/130	NR	150	NR	35	NR	35	NR	NR	45
Germany	160	105[3]	300[4]/200	80[3]	75[4]/50	20[3]	NR	NR	NR	45
Hungary	130	130	200	200	75	75	200	200	0.6	45
Iceland	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ireland	200	100	200	100	50	35	NA	NA	0.4/0.3	50
Italy	130	100	150	110	50	35	35	25	0.7	45
Latvia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lithuania	130	130	200	200	50	50	NR	NR	NR	45
Luxembourg	160	130	300	150	75	35	NR	NR	NR	55
Norway	130/100[2]	NR	150/100[2]	NR	50	NR	NR	NR	NR	50
Poland	130/160[1]	100/130[1]	250	200	50	35	NR	NR	0.40/0.50[1]	0.45[5]
Portugal	NR	100	200	100	NR	NR	NR	NR	0.3	45
Romania	160	160	300	300	75	75	NR	NR	0.6	45
Slovakia	160	100	300	100	35/50[6]	35/50[6]	35/50[6]	35/50[6]	0.3	45
Slovenia	160	130	300	100	50	35	NR	NR	0.4	45
Spain	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	130	NR	150	NR	35	NR	NR	NR	NR	50
The Netherlands	130	<130	100	<100	35	<35	NR	NR	0.4/0.6	55

NM – new markings; RE – minimal value for renewal; NR – not requested; NA – not applicable; ND – no data
* Expressways (2+2 and 2+1 lane roads)
1 - first values for asphalt, second for concrete; 2 – first value for white, second for yellow markings; 3 - recommended values according to ZTV M 13 for the renewal of used road markings. ZTV M 13 also defines (higher) values for the end of the warranty period. 4 - first value only for tapes; 5 - PFT units; 6 – second value for plastic road markings

Minimal values of daytime and night-time visibility (for condition of wetness and rain), luminance factor and skid resistance for road markings on primary roads

	Primary roads									
Country	**Qd – NM**	**Qd - RE**	**R_L – NM**	**R_L - RE**	**RW – NM**	**RW - RE**	**RR – NM**	**RR - RE**	**β**	**SRT**
Austria	NA	NA	NA	NA	NA	NA	NA	NA	NR	
Belgium	160/130[1]	160/130[1]	150	150	NR	NR	NR	NR	NR	45
Bulgaria	160	130	300	150	50	35	NR	NR	0.5	55
Croatia	130	100	200	100	50[2]	35[2]	NR	NR	0.4	45
Cyprus	130/100[3]	NR	200/150[3]	NR	35	NR	NR	NR	LF6	45
Estonia	130	NR	150	100	35	NR	35	NR	NR	55
Finland	130	130	150	100	NR	NR	NR	NR	0.8	45
France	100/130	NR	150	NR	35	NR	35	NR	NR	45
Germany	160	105[4]	300[5]/200	80[4]	75[5]/50	20[4]	NR	NR	NR	45
Hungary	130	130	150	150	50	50	150	150	0.6	45
Iceland	130	NR	150	100	NR	NR	NR	NR	NR	0.52[6]
Ireland	200	100	200	100	50	35	NA	NA	0.4/0.3	50
Italy	NR	100	NR	150	NR	35	NR	25	0.87	45
Latvia	100	100	150	150	50	50	NR	NR	5	45
Lithuania	130	130	200	200	50	50	NR	NR	NR	45
Luxembourg	160	130	200	100	50	25	NR	NR	NR	45
Norway	130/100[3]	NR	150/100[3]	NR	50	NR	NR	NR	NR	50
Poland	130/160[1]	100/130[1]	250	200	50	35	NR	NR	0.40/0.50[1]	0.45[6]
Portugal	160	100	200	100	50	35	50	35	0.6	45
Romania	160	160	300	300	75	75	NR	NR	0.6	45
Slovakia	160	100	300	100	35/50[7]	35/50[7]	35/50[7]	35/50[7]	0.3	45
Slovenia	160	130	300	100	50	35	NR	NR	0.4	45
Spain	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sweden	130	NR	150	NR	35	35	NR	NR	NR	0.5[6]
The Netherlands	130	<130	100	<100	35	<35	NR	NR	0.4/0.6	55

NM – new markings; RE – minimal value for renewal; NR – not requested; NA – not applicable; ND – no data
1 - first values for asphalt, second for concrete; 2 – only for Type II markings; 3 – first value for white, second for yellow markings; 4 - recommended values according to ZTV M 13 for the renewal of used road markings. ZTV M 13 also defines (higher) values for the end of the warranty period; 5 – first value only for tapes; 6 – PFT units; 7 - second value for plastic road markings

ANNEX 1.4: HISTORICAL AND CURRENT UNIT COSTS OF A FATAL, SERIOUS AND SLIGHT INJURED PERSON IN EACH MEMBER STATE

Unit costs of a fatal, serious and slight injured person in each Member State in 2015 ((Wijnen et al., 2017)*.*

	Costs per casualty (2015) in Euro		
Country	**Fatality**	**Serious injury**	**Slight injury**
Austria	3.014.655,00	381.285,00	26.880,00
Belgium	2.021.091,00	307.364,00	19.766,00
Bulgaria	1.355.315,00	220.390,00	57.267,00
Croatia	2.230.967,00	290.042,00	22.259,00
Cyprus	1.027.088,00	135.535,00	9.921,00
Estonia	2.819.426,00	959.011,00	36.802,00
Finland	2.340.452,00	671.383,00	29.111,00
France	2.944.662,00	368.029,00	14.070,00
Germany	1.177.194,00	119.480,00	4.954,00
Hungary	2.147.976,00	501.194,00	553,00
Iceland	2.861.281,00	364.914,00	71.742,00
Ireland	1.965.163,00	225.511,00	20.860,00
Italy	1.615.566,00	211.860,00	18.245,00
Latvia	1.141.935,00	28.205,00	296,00
Lithuania	988.981,00	89.804,00	NA
Luxembourg	NA	NA	NA
Norway	2.690.394,00	845.812,00	52.970,00
Poland	814.504,00	975.074,00	11.536,00
Portugal	838.109,00	136.365,00	35.391,00
Romania	NA	NA	NA
Slovakia	652.238,00	141.504,00	20.767,00
Slovenia	2.118.429,00	247.550,00	24.412,00
Spain	1.592.359,00	254.777,00	6.938,00
Sweden	2.160.235,00	399.728,00	19.561,00
The Netherlands	2.504.928,00	269.149,00	6.031,00

Inflation level in Member States 2015 compared to 2022 (Eurostat, 2022; Inflation.eu, 2022, 2022).

Country	Inflation 2015	Inflation 2022	Difference	Note
Austria	100	106,28	6,28	
Belgium	100	109,32	9,32	
Bulgaria	100	106,78	6,78	EU average no MS specific figure available
Croatia	100	106,78	6,78	EU average no MS specific figure available
Cyprus	100	106,78	6,78	EU average no MS specific figure available
Estonia	100	106,78	6,78	EU average no MS specific figure available
Finland	100	105,45	5,45	
France	100	104,75	4,75	
Germany	100	106,69	6,69	
Hungary	100	109,07	9,07	
Iceland	100	104,69	4,69	
Ireland	100	109,60	9,60	
Italy	100	106,33	6,33	
Latvia	100	106,78	6,78	EU average no MS specific figure available
Lithuania	100	106,78	6,78	EU average no MS specific figure available
Luxembourg	100	107,69	7,69	
Norway	100	106,78	6,78	EU average no MS specific figure available
Poland	100	110,23	10,23	
Portugal	100	105,75	5,75	
Romania	100	106,78	6,78	EU average no MS specific figure available
Slovakia	100	109,63	9,63	
Slovenia	100	107,01	7,01	
Spain	100	108,07	8,07	
Sweden	100	105,76	5,76	
The Netherlands	100	109,58	9,58	

Unit costs of a fatal, serious and slight injured person in each Member State in 2022

	Costs per casualty (2022) in Euro		
Country	**Fatality**	**Serious injury**	**Slight injury**
Austria	3.203.975,33	405.229,70	28.568,06
Belgium	2.209.456,68	336.010,32	21.608,19
Bulgaria	1.447.205,36	235.332,44	61.149,70
Croatia	2.382.226,56	309.706,85	23.768,16
Cyprus	1.096.724,57	144.724,27	10.593,64
Estonia	3.010.583,08	1.024.031,95	39.297,18
Finland	2.468.006,63	707.973,37	30.697,55
France	3.084.533,45	385.510,38	14.738,33
Germany	1.255.948,28	127.473,21	5.285,42
Hungary	2.342.797,42	546.652,30	603,16
Iceland	2.995.475,08	382.028,47	75.106,70
Ireland	2.153.818,65	247.160,06	22.862,56
Italy	1.717.831,33	225.270,74	19.399,91
Latvia	1.219.358,19	30.117,30	316,07
Lithuania	1.056.033,91	95.892,71	NA
Luxembourg	NA	NA	NA
Norway	2.872.802,71	903.158,05	56.561,37
Poland	897.827,76	1.074.824,07	12.716,13
Portugal	886.300,27	144.205,99	37.425,98
Romania	NA	NA	NA
Slovakia	715.048,52	155.130,84	22.766,86
Slovenia	2.266.930,87	264.903,26	26.123,28
Spain	1.720.862,37	275.337,50	7.497,90
Sweden	2.284.664,54	422.752,33	20.687,71
The Netherlands	2.744.900,10	294.933,47	6.608,77

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