Safety implications of higher levels of automated vehicles: a scoping review

Peer-reviewed author version

TAFIDIS, Pavlos; FARAH, Haneen; BRIJS, Tom & PIRDAVANI, Ali (2022) Safety implications of higher levels of automated vehicles: a scoping review. In: Transport reviews, 42 (2) , p. 245-267.

DOI: 10.1080/01441647.2021.1971794
Handle: http://hdl.handle.net/1942/34781

Safety Implications of Higher Levels of Automated Vehicles: A Scoping Review

Pavlos Tafidis[a]*, Haneen Farah[b], Tom Brijs[c] and, Ali Pirdavani[a,c]

[a] *UHasselt, Faculty of Engineering Technology, Agoralaan, 3590 Diepenbeek, Belgium;*

[b] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, ,Department of Transport and Planning, Stevinweg 1, 2628 CN Delft, The Netherlands;*

[c] *UHasselt, Transportation Research Institute, Agoralaan, 3590 Diepenbeek, Belgium*

*pavlos.tafidis@uhasselt.be, UHasselt, Faculty of Engineering Technology, Construction Engineering Research Group, Agoralaan, B-3950 Diepenbeek, Belgium

Safety Implications of Higher Levels of Automated Vehicles: A Scoping Review

Automated vehicles (AVs) promise to improve road safety, reduce traffic congestion and emissions, and enhance mobility. However, evidence regarding their safety benefits has not been systematically investigated and documented. In this study, we utilise a scoping review approach to investigate and synthesise the existing literature on higher levels of AVs' safety implications. This aids future relevant studies by identifying the research gaps and reporting the methodological approaches used. The review focused not only on peer-reviewed articles but also on grey literature to provide a comprehensive overview of the current research state. In total, 5724 articles were identified, and 4167 records were screened after duplicates and dual publications removal, from which 27 were found eligible for review. Ultimately, 24 studies met all the inclusion criteria and were considered for the review. The reported evidence was focused on changes in road safety levels after the deployment of AVs in transport networks. The data was extracted and charted by one reviewer using tables to create a descriptive summary of the results and address the scoping review's questions and objectives. In general, the findings suggest that AVs hold the potential to improve the overall safety on roads, although the existing evidence is not mainly based on real data but assumptions regarding vehicles' capabilities and behaviour. The limited number of studies and the fact that all of them were published or conducted after 2014 indicate that the research on AVs' safety impacts is just emerging.

Keywords: scoping review; automated vehicles; road safety; safety evaluation; impact assessment

Introduction

The concept of automated vehicles (AVs) dates back to the 1920s, when the first radio-controlled vehicles were designed (Bimbraw, 2015). During the following decades, various initiatives were also recorded; Norman Bel Geddes at General Motors' exhibit (1939); General Motor (1958); Carnegie Mellon University (1984); Mercedes-Benz and Bundeswehr University Munich (1987) (Ondruš, Kolla, Vertaľ, & Šarić, 2020). In this era, the 21st century, the Society of Automotive Engineers (i.e., SAE International), among other organizations (e.g., German Federal Highway Research Institute (BASt) (Gasser and Westhoff, 2012) and National Highway Traffic Safety Administration (NHTSA) (NHTSA, 2013)), have defined different levels of driving automation based on vehicle's operation and driver's interference (SAE, 2018).

Level 0 refers to the conventional vehicles where the human driver is responsible for the entire dynamic driving task (DDT). Level 1 vehicles are already on public roads as most modern passenger cars incorporate some type of adaptive cruise control or lane departure warning systems. Nowadays, cars qualified for level 2 of automation are also available to the public. Various automobile companies have already produced vehicles merging two or more automated technologies that can function simultaneously. Vehicles of level 1 or 2 support the driver during the DDT but cannot perform the complete DDT as the drivers are always responsible for performing the object and event detection and response (OEDR) subtask. Level 3, or the so-called “conditional automation”, is where the vehicle will independently perform various tasks. At this level, the entire DDT, as well as OEDR can be performed by the vehicle with the expectation that the human driver must be ready to intervene upon request. At this point, the first issues have been raised concerning the safety risks of AVs. The anticipated interaction between the human and the system, the potentially mixed traffic flow, and the infrastructure requirements challenge level 3 automation deployment. Because of the aforementioned unsolved matters, different companies decided to skip this level and pursue the next level (Faggella, 2020). At level 4, cars will be ready to travel without the need for human interference in multiple scenarios and on different road types, although the driver will still have the option to take back control. In the highest level of automation (i.e., level 5 or full automation), the car will drive in every condition without requiring drivers' attention.

These vehicles do not necessarily require a steering wheel or pedals, and they most likely will function more like a passenger transport rather than conventional cars. In the higher levels of automation (Levels 4 and 5), the automated driving system takes over the complete DDT and the DDT fallback without any expectation or request to intervene from the user.

The increasing context of the presence of AVs on transport networks has given rise to new opportunities and challenges in the promotion of sustainable mobility (Olia, Abdelgawad, Abdulhai, & Razavi, 2016) and increase of road capacity (Fagnant and Kockelman, 2015; Pereira, Anany, Pribyl, Prikryl, & Ruzicka, 2017), while there is a consensus that they will play a decisive role in improving traffic safety (Penmetsa, Adanu, Wood, Wang, & Jones, 2019). This is because the system is less human-dependent, and human error is a significant cause of road crashes (Singh, 2015). Having said that, the anticipated benefits are mainly untested and contain a great deal of speculation. To a great extent, these evaluations have ignored the possibility of the emergence of new types of crashes. Besides the fact that extensive real-world data is not yet available, technical and legal obstacles or ethical issues regarding their implementation make AVs' evaluation even more challenging (Liljamo, Liimatainen, & Pollanen, 2018).

Existing evaluation methodologies were mainly developed to assess the functionality of low automated technologies, for instance, lane departure warning, forward collision warning, adaptive cruise control, cooperative adaptive cruise control, and lane-keeping assistance (Vasebi and Hayeri, 2020), which are characterized by different driver engagement time compared to high-level automated functions leading to indisputable different evaluation requirements (A. Zlocki et al., 2014). Applying existing approaches under real-world conditions is already considered costly and time-consuming, making them unsuitable for AVs (Adrian Zlocki, Eckstein, & Fahrenkrog, 2015).

Concerning the AVs' safety impact assessment, methodologies that rely on assumptions regarding the driving behaviour of AVs or users' preferences are applied in the literature (e.g., Kockelman et al., 2016; Morando, Tian, Truong, & Vu, 2018; Tibljas, Giuffre, Surdonja, & Trubia, 2018). These approaches mainly focus on estimating the number and severity of conflicts after introducing AVs in traffic streams and the number of preventable accidents/fatalities or the changes in crash/fatality rates by coupling road traffic simulation software with surrogate safety measures or using effectiveness scenarios. In simulation studies, the results are heavily dependent on each parameter's value as different sets can define the vehicles' longitudinal and lateral behaviour differently (e.g., headway time, following variation). Limitations exist as well in the calibration and validation process of the models as no real-world trajectory data is available to model the new type of vehicles efficiently. It should also be highlighted that only in few cases, the base model (i.e., the current situation with only human-driven vehicles), is subjected to calibration and validation procedure (e.g., Granados et al., 2018; Tafidis et al., 2018) as authors tend to use the default parameters of the models. At the same time, accident analysis studies containing safety effectiveness evaluations are based on assumptions regarding the capabilities of various automated technologies raising arguments if the results are valid, applicable, and useful. They often assume a faultless operation without considering weather, road and vehicle conditions or system failure and other potential risks, and a 100% market penetration scenario that does not represent a realistic or short-term scenario (e.g., Fagnant and Kockelman, 2014; Luttrell, Weaver, & Harris, 2015; Combs, Sandt, Clamann, & McDonald, 2019). The development and application of new approaches to overcome the barriers mentioned above are fundamental to assess AVs' operation and interactions with the road environment under different conditions and scenarios.

In the literature, various initiatives tried to identify and report research on AVs (Gandia et al., 2018), their implications on travel behaviour and land use (Soteropoulos, Berger, & Ciari, 2018), infrastructure design (H. Farah, S. Erkens, T. Alkim, & B. van Arem, 2018), congestion and accessibility (Cohen and Cavoli, 2018), safety, liability, privacy, cybersecurity and industry influence (Taeihagh and Lim, 2019), health (Dean et al., 2019; Sohrabi, Khreis, & Lord, 2020), but to the best of our knowledge no relevant review study exists on AVs' impact on road safety performance.

In this study, we employ a scoping review approach to systematically document and synthesise the existing research evidence related to higher levels AVs' safety implications and provide the foundation for future efforts by identifying key concepts, methodological gaps, and reporting the most common practices in the topic area. For this purpose, the following research question is formulated: What evidence exists on higher levels of AVs' safety implications?

In this study, we opted for a scoping review instead of a systematic review as our main objective is to answer a general question on a given topic by providing a detailed overview of the available literature area (Munn et al., 2018). More specifically, we aim at identifying and mapping the existing evidence and present how research has been conducted in this area. As it is clearly stated in the literature, scoping reviews are valuable tools to report the research evidence on an emerging topic, present the key concepts and methodological approaches and identify knowledge gaps (Arksey and O'Malley, 2005), compared to systematic reviews that aim to provide a synthesis and critical appraisal of the existing evidence (Munn et al., 2018). Since AVs are still a developing technology with ongoing research, and the available evidence is still limited and has not yet comprehensively been reviewed, a scoping review study is believed to be the most suitable approach to present existing literature due to its very descriptive nature compared to a systematic review.

The focus of the study is on AVs of SAE levels 4 and 5 as lower levels of automation (i.e., levels 1 and 2) are already available on public roads, and a significant amount of research has been conducted on evaluating their impact with the use of simulations and real-world data. Concerning level 3 vehicles, there is a great possibility that the technology could never reach maturity due to the delineation of responsibility issues between the human and the system. Connectivity capabilities are also not included in the current work since the deployment of AVs will require fewer investments with respect to physical and digital infrastructure and will provide fewer hardware and software security risks (Coppola and Silvestri, 2019). Although connectivity in vehicles is a mature technology, the diffusion of the technology in the market is still not considerable (Coppola and Silvestri, 2019), mainly due to the requirements that have to be met, especially on road infrastructure (Farah, Erkens, Alkim, & van Arem, 2018).

The rest of the paper is structured as follows: the following section describes the methodological approach adopted, while afterwards, the extent of research on safety implications of AVs is documented, and an overview of the scientific literature is provided. Then, in the discussion section, we focus on synthesising and comparing the existing evidence and providing recommendations for future research. Finally, the last section contains the conclusions.

Methodology

While there is no universally recognized definition or an established procedure for a scoping review, its primary purpose is to provide a broad descriptive overview of a topic by accumulating the existing literature and mapping their results (Peterson, Pearce, Ferguson, & Langford, 2017; Pham et al., 2014). The different steps of the methodological approach that we followed in conducting and reporting the current study are listed below, while the following sections explain each of these steps in detail. The different steps of the methodological approach are:

- Eligibility Criteria
- Information Sources
- Search Process
- Selection of Sources of Evidence
- Data Charting Process
- Data Items
- Synthesis of Results

The methodology was built upon the PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Preferred Reporting Items for Systematic Review and Meta-Analysis (Tricco et al., 2018) to achieve complete and transparent results. The PRISMA-ScR is a 22-item reporting checklist developed in consultation with an international panel of experts to contribute to research and scientific publications.

Eligibility Criteria

In this research, reviewed studies were required to estimate AVs' (SAE level 4-5) impact on safety performance (quantitative or qualitative). Safety performance was defined as any change in road safety by means of the number of crashes or the number of killed or injured people (ETSC, 2001). In addition, studies that reported the potential impacts in monetary terms or through the number of conflicts were also considered. Only peer-reviewed documents published in English up to and including 2020 were selected for this review. However, to provide a complete overview of the current state-of-the-art, grey literature, and unpublished material were also reviewed and mentioned accordingly. Examples of grey literature include projects, theses, conference proceedings, technical and commercial documentation (Haddaway and Bayliss, 2015). Papers or studies dealing with traffic performance, environmental or other implications of AVs were excluded.

Information Sources

The following bibliographic databases were used to identify potential sources of evidence: Science Direct, Transportation Research International Documentation (TRID), and Web of Science. In order to achieve a comprehensive and precise search, a two-step strategy was adopted. More specifically, after identifying peer-reviewed articles (i.e., step 1), two more information sources were examined (i.e., step 2): i) grey literature and ii) documents suggested by the authors.

The grey literature search is considered challenging as there are no equivalent bibliographic databases, while respective sources often lack advanced search and export features. In addition, it is worth mentioning that much of the literature on transportation is grey literature, i.e., published by non-profits, research agencies, governments, while primary transportation databases, e.g., TRID and Web of Science, include many citations characterized as grey literature. Nevertheless, to supplement our search, we conducted web searching and examined dedicated grey literature, web-based catalogues and databases, and targeted websites.

In order to search the web, we decided to use Google Scholar. Compared to Google or any other web-based search engine, this web-based academic search engine is widely utilised in research for both academic and grey literature since it provides more search and export capabilities.

The identification of grey literature databases was based upon the suggestions of Hasselt University Library. It is worth mentioning that the majority of grey literature catalogues focused on health sciences, and only the following was found containing documents from various fields:

- Open Grey (http://www.opengrey.eu/): An open-access database providing access to 700.000 bibliographical references of grey literature produced in Europe.

Finally, the following list contains websites that were identified as relevant to the subject of the review or were suggested by the authors of the current study:

- etsc.eu: European Transport Safety Council is a Brussels-based independent non-profit making organization.
- op.europa.eu: The publication office of European Union
- highways.dot.gov: United States Department of Transportation – Federal Highway Administration.

Search Process

We set up different but equivalent search strings due to each database's different capabilities and limitations. Keywords defining our research topic's content suggested by the authors and relevant synonyms or variants identified from the Cambridge Online Dictionary (https://dictionary.cambridge.org/) were linked using Boolean operators and were applied to provide results. The less correct terminologies that are widely used in the literature to describe AVs, such as "autonomous", "driverless", "driver-less", or "self-driving" vehicles (Shladover, 2018), were also considered.

In the literature, relevant keywords can include different spellings, variants of keywords, synonyms, and related concepts. Their identification can be performed through dictionaries, encyclopaedias, textbooks, other review papers, text mining tools. However, no approach can assure that the final search will be broad enough to locate every available source specific to the topic.

The entire search strategy is provided as a supplemental file to allow easy replication. No other search limits were used during the process.

Finally, in relevant review studies and included studies, the search procedure was supplemented by screening the reference lists, i.e., backward snowballing (Jalali and Wohlin, 2012). In addition, in cases of projects, publications and deliverables were scanned, and for conference proceedings, the included papers' titles and abstracts were examined. The literature search was conducted from 20th to 27th August 2020. The strategy was developed and executed by the authors' team.

Selection of Sources of Evidence

One reviewer conducted the screening and selection processes. During this phase, relevant documents were initially identified by scanning the title and abstract of each reference. Following the preliminary assessment, the full articles were reviewed for eligibility. The final selection was discussed and approved by all the authors.

Data Charting Process

The authors' team agreed on the data charting process and form. The data items (explained below) were extracted, charted, and stored by one reviewer in Microsoft Excel and were discussed, updated, and validated in collaboration with the rest of the authors.

Data Items

The data were abstracted on the general characteristics of each study (i.e., authors, year of publication, academic source or grey literature, the discipline of the journal/conference, reference country), their study designs (i.e., methodological approach, the scale of application, mobility concept, traffic conditions, level/type of AVs, penetration rate), and finally, their findings, metrics that were adopted, and assumptions, limitations or uncertainties as stated by the authors of the identified papers.

Synthesis of Results

Results were synthesised and mapped based on the extracted and charted data. More specifically, studies were clustered by the methodological approach they have adopted, the scale of application, study design, metrics used, and then the broad findings were summarised accordingly. Finally, tables and graphs were used to represent the identified evidence visually.

Results

Selection of Sources of Evidence

The search process returned 5706 references, which were then imported into the EndNote X9 reference management software package (Clarivate Analytics, 2019). Duplicates were removed, either automatically or manually, and resulted in 4167 unique references that went through the screening process. Additionally, 18 studies that were not identified through the database searching but identified during the screening process or suggested by authors were also included, so that in total, 4185 studies were qualified for the screening process. From the additional 18 studies, five potential unscanned studies were identified in relevant review studies, five more potential documents that were not scanned previously were identified as publications or deliverables of projects, two potential unscanned documents were identified in conference proceedings. Finally, six documents were suggested by the authors for revision, mainly students' theses from university repositories and relevant reports.

Studies excluded from the final round of review were mainly focused on the low levels of automation (level 1-2), semi-automation (level 3), or assessing connectivity that was out of this study's scope. Other criteria that led to rejection were: i) no reported safety implications, ii) findings not about road safety, and iii) studies not relevant to automation in road vehicles. Following the preliminary assessment, the full articles of 27 studies were reviewed for eligibility. As a result, only 24 studies were included in the review, while 3 were excluded as they did not fulfil all the required inclusion criteria. Figure 1 presents the selection process of sources of evidence.

Figure 1. Selection Process Flow Diagram (based on Moher et al., 2015)

Characteristics of Sources of Evidence

The review identified 24 studies that reported road safety implications of AVs. The general characteristics of each study are listed in Table 1. The study design of each work is presented in Table 2, and the major findings are shown in Table 3. All studies presented the results concerning the changes in safety performance after the introduction of AVs.

Table 1. General Study Characteristics.

Table 2. Study Design

Table 3. Study Findings.

Synthesis of the Results

As mentioned above, in this scoping review, we identified 24 studies estimating AVs' safety implications between 2014 and 2020. Our findings indicate that AVs' impact on road safety is an emerging topic as no relevant studies were conducted before 2014, while most of these studies were performed in the United States (n = 11).

Regarding the source of each piece of evidence we found, 10 studies are peer-reviewed articles, while 14 studies are considered grey literature (10 conference proceedings and 4 reports). The peer-reviewed articles were published in transportation, medicine, safety, or cross-disciplinary journals showing the topic's multidisciplinary nature.

Different research approaches were employed to estimate the safety impact of AVs, including traffic simulation (n = 15), accident analysis (n = 8), and accident prediction models (n = 1). As expected from the findings, it is evident that the estimation of AVs' safety implications based on accident analysis is applied on a big scale (i.e., road segment or national road network). At the same time, traffic simulation is mainly limited to an intersection or a road segment level. Most studies focused on rural roads (n = 5) where the interactions with other road users are limited, while the impact of AVs on urban networks (n = 4) or sub-urban intersections (n = 4) was also of great interest.

It was also interesting to examine under what mobility concept AVs implications were estimated. The identified studies focus on motorized traffic, with only 11 out of the 23 studies (one study does not provide information), i.e., 47.83%, including cyclists or pedestrians in their analysis. In urban areas, 2 out of 6 documents, i.e., 33.33%, did not consider cyclists or pedestrians in their study.

For the studies that used traffic simulation as their method, the study designs' main characteristics, i.e., traffic conditions and penetration rates, are presented in Figure 2. It can be observed that most studies selected to investigate AVs' impact on traffic streams under high flow traffic conditions and by assuming a full market penetration rate.

Figure 2. Study Designs' Main Characteristics

Continuing with the review's main objective, 20 studies reported positive safety implications, 8 negative and 6 neutral/other. Expectedly, the great majority of the studies noted a positive impact concerning road safety. However, it would be interesting to analyse the particular characteristics of the studies that declared negative findings. Table 2 shows us that all the studies that reported potential negative impacts measured the AVs' impact utilizing traffic microsimulation techniques. The majority of them identified that AVs' anticipated implementation would reduce the safety performance at intersections/roundabouts (n = 4) and at low penetrations rates (n = 4). However, only one study reported solely negative findings (Tibljas et al., 2018). One more study stated that AVs' impact (positive or negative) depended on the examined case study (Xie et al., 2019). Finally, two studies mentioned adverse safety effects to other road users as a side effect of AVs' deployment (Kitajima, Shimono, Tajima, Antona-Makoshi, & Uchida, 2019; Thompson, Read, Wijnands, & Salmon, 2020).

A more detailed analysis of AVs' reported safety implications further demonstrates their strong relationship with the applied methodological approach and the assumptions made within each study. More specifically, studies utilizing accident analysis followed a closely similar procedure that can be summarised in the following steps: i) identification of AVs technological capabilities and functions; ii) correlation of technologies and functions with specific crash types; iii) accident data analysis to define preventable crashes; iv) consideration of different effectiveness scenarios or market penetration rates and; v) estimation of preventable crashes or other relevant metrics. Studies that followed the abovementioned approach only reported safety benefits as they widely proceeded with assumptions that idealize the future transport paradigm. Particularly, AVs are assumed to function faultlessly and reliably and operate in all weather and light conditions (Fagnant and Kockelman, 2014; Luttrell, Weaver, & Harris, 2015; Combs, Sandt, Clamann, & McDonald, 2019; Utriainen and Pollanen, 2020). Moreover, crash rates for non-AVs are assumed constant (Fagnant and Kockelman, 2014; Casualty Actuarial Society, 2014; Luttrell, Weaver, & Harris, 2015; Combs, Sandt, Clamann, & McDonald, 2019) and potential new crashes, which AVs could cause are not taken into account (Kühn and Bende, 2020; Combs, Sandt, Clamann, & McDonald, 2019; Utriainen and Pollanen, 2020). Furthermore, the severity distribution of all crashes was assumed unchanged (Fagnant and Kockelman, 2014; Luttrell, Weaver, & Harris, 2015). Nevertheless, various studies (Casualty Actuarial Society, 2014; Detwiller and Gabler, 2017; Utriainen and Pollanen, 2020) stated that even in the case of AVs faultless operation, the new technology cannot prevent all types of crashes. More specifically, most of the studies assumed the safety effectiveness of AVs to be 100% with boundary conditions to be taken into account (Casualty Actuarial Society, 2014; Combs, Sandt, Clamann, & McDonald, 2019; Kühn and Bende, 2020; Utriainen and Pollanen, 2020), or only specific technologies of AVs or combination of them were examined (Rau, Yanagisawa, & Najm, 2015; Kühn and Bende, 2020). Included studies mainly assessed AVs' impact concerning all types of crashes, although initiatives focused on specific crash types (e.g., crashes involving pedestrians (Detwiller and Gabler, 2017; Utriainen and Pollanen, 2020; Combs, Sandt, Clamann, & McDonald, 2019) or examining different

AVs' driving behaviours (Detwiller and Gabler, 2017; Utriainen and Pollanen, 2020;). Almost all studies also assumed a 100% market penetration scenario of AVs considering a long-term vision for the transport sector. Different penetration rates were only considered in Fagnant and Kockelman (2014) and; Luttrell, Weaver, & Harris (2015) to simulate short, mid, and long-term implementation scenarios.

On the contrary, the safety implications of AVs significantly differed across included traffic simulation studies. Results are greatly dependent on the scale of application, the study purpose, the simulated scenarios, the deployed driving behaviour models for AVs and human-driven vehicles, the calibration and validation procedure of the models. Moreover, since traffic simulation software cannot produce crashes, different SSMs were applied to return the number of potential conflicts. Therefore, it is difficult to identify common and specific patterns among available evidence. Moreover, it appears that AVs' expected shorter headway is the main reason behind the increase in the number of potential conflicts (Arvin, Kamrani, Khattak, & Rios-Torres, 2018; Morando, Tian, Truong, & Vu, 2018; Tibljas, Giuffre, Surdonja, & Trubia, 2018; Li and Wagner, 2019; Xie et al., 2019)). Concerning the positive safety implications of AVs, the majority of the identified studies found that in high market penetration rates (Kockelman et al., 2016; Arvin, Kamrani, Khattak, & Rios-Torres, 2018; Morando, Tian, Truong, & Vu, 2018; Li and Wagner, 2019) and at road segments (Kakimoto, Iryo-Asano, Orhan, & Nakamura, 2018; Morando, Tian, Truong, & Vu, 2018; Yu, Tak, Park, & Yeo, 2019; Zhu and Krause, 2019) the new technology returned significant safety benefits.

The development and deployment of an accident prediction model (Kalra and Groves, 2017) to examine AVs' safety performance took into account various factors, e.g., changes in travel demand, changes in the safety performance of human-driven vehicles, the timing of AVs market introduction and the penetration rate, the evolution of

AVs' safety performance and the upgradeability of AVs fleet during the time. However, it should be mentioned that the main objective of the study was to validate the application of the suggested model and not to assess AVs' operation.

Finally, as mentioned before, the AVs' safety impact was quantified using different metrics to evaluate their road safety performance and compare it to that of the human-driven vehicles. In this review, different safety performance metrics that were utilised from the included studies were collected and reported. Figure 3 presents the effort of mapping and grouping the respective findings. It can be noticed that a wide range of different metrics was proposed and used for measuring the safety performance of both AVs and non-AVs. Most studies tried to measure AVs' impact by estimating the average, annual, or total number of crashes/collisions. In studies that based their approach on accident analysis and effectiveness scenarios, mainly historical crash data obtained by public authorities were used to allow the safety evaluation. In the same way, other studies estimated the number of preventable accidents/fatalities or the changes in crash/fatality rates that could be achieved by vehicles equipped with automated technologies and the human factor out of the loop. Moreover, the deployment of traffic simulation software combined with surrogate safety measures allowed assessing safety performance, either by estimating the number and severity of potential conflicts or by directly observing the changes in different surrogate safety measures.

Figure 3. Adopted Metrics per Study

Discussion

This study has demonstrated that there are limited publications on AVs' implications on road safety. Specifically, the review identified only 24 published articles in peer-reviewed journals and grey literature that examined how levels 4 - 5 of automation will impact safety performance in transport networks. The available evidence has mainly reported the AVs' impact in terms of the number of potential conflicts or crashes, although the results varied, as did the research approaches and study cases across different studies. Also, the identified literature was published after 2014, suggesting that the research on AVs' safety implications has just emerged.

Furthermore, this review has highlighted the gaps in the available literature concerning AVs' impacts on cyclists' and pedestrians' safety. Vulnerable road users are potentially the most critical element in an urban road environment, and their safety is of great concern (Hamed, 2001; Vanparijs, Int Panis, Meeusen, & de Geus, 2015). For that reason, they cannot be excluded from any safety analysis, particularly in urban areas. This should be further explored in future studies.

The safety implications identified were mainly established in developed countries, and in the context of mixed traffic, given different rates of AVs' market penetration. However, no study was found that examines the AVs' impacts in developing countries where road fatalities and injury rates are significantly higher (Jadaan, Al-Braizat, Al-Rafayah, Gammoh, & Abukahlil, 2018). Moreover, the effect of potential AVs' applications such as car-sharing, AVs-lanes, or entire AVs-zones in city centres has not yet been studied. Notably, in the available literature, the impact of different road geometry on AVs operation is limited.

It should also be considered that different measures were used across the literature to estimate the AVs' safety impacts. Namely, studies used the number of conflicts or crashes, the severity level of crashes, collision risk, different surrogate measures, fatality rates. It is difficult to draw a useful interpretation with consistency, as too many metrics were used across the reviewed studies. We should mention that the adopted metrics were primarily developed to assess human-driven vehicles' safety performance. Hence, their applicability and validity for AVs should be examined.

The existing evaluation methods can be mainly classified into two categories with different validity levels. These categories range from virtual evaluation in traffic simulation to real-world evaluation based on historical data. Unfortunately, neither full real-world evaluations nor in-field operational tests are reported in the existing literature since the examined technology is not available. For that reason, researchers sometimes have to proceed with bold assumptions in order to provide results.

Traffic micro-simulation software coupled with surrogate safety measures allows a proactive safety evaluation (Mahmud, Ferreira, Hoque, & Tavassoli, 2019), focusing on vehicle interactions and understanding AVs' ramifications on transport networks until extensive real-world data becomes available. However, the results heavily depend on the driving behaviour logics defined in the simulation (Punzo and Ciuffo, 2009) and traffic composition. Future research should focus on optimising AVs' driving behaviour models to obtain more reliable and realistic results until extensive real-world data becomes available. This can be proved helpful for further research on roads' geometric design or road infrastructure requirements for AVs. Another prominent gap that we identified concerning the AVs' simulations is that the current methodologies cannot capture severe weather conditions or road gradients, impacting vehicles' efficiency and performance (Khoury, Amine, & Abi Saad, 2019; Zang et al., 2019), especially the performance of lane-keeping systems (Farah et al., 2020; García and Camacho-Torregrosa, 2020; Reddy, Farah, Huang, Dekker, & Van Arem, 2020).

Another area that lacks investigation is the potential adaptation of other road users to AVs (Schoenmakers, Yang & Farah, 2021). There is a great possibility that many of the potential benefits of the new technology will be offset by the future risky or aggressive behaviour of human drivers or pedestrians relying on AVs' capabilities. Early investigations of safety reports from road tests with AVs of levels 3 and 4 demonstrated that critical situations were mainly the result of road rule violations or careless behaviour of other road users, i.e., human-drivers, pedestrians, and cyclists (Schwall, Daniel, Victor, Favaro, & Hohnhold, 2020). The findings support the available evidence showing that even the faultless operation of AVs cannot eliminate all potential crashes (Casualty Actuarial Society, 2014; Detwiller and Gabler, 2017; Utriainen and Pollanen, 2020) as the coexistence of AVs and human-driven vehicles on public roads will create new challenges. At the same time, the deployment of the new technology may also raise travel demand and potentially the number and distance of trips. In addition, the new type of vehicle will probably increase the mobility of the elderly and people with disabilities (Millonig, 2019). Consequently, the rise in total vehicle miles travelled could negatively impact traffic safety performance.

It should also be highlighted that the available evidence overwhelmingly ignored the development of new types of accidents that may emerge, mainly in mixed traffic conditions. Automated vehicles' operation is based on the combination of different sensing and computing technologies. For instance, different sensors are responsible for object recognition in the road environment and provide the vehicle with crucial information for its safe navigation (Pendleton et al., 2017). Therefore, potential system operation failure will result in unexpected safety risks. In Boggs, Arvin, & Khattak (2020), the authors investigated the California Department of Motor Vehicle disengagement and crash reports (concerning mainly Level 3 AVs) and identified six distinctive types of disengagements, which mainly involve discrepancies in vehicles' operation. More specifically, AVs can experience control discrepancies, environmental and other road user discrepancies, hardware and software discrepancies, perception discrepancies, planning discrepancies, and operator takeover (that is not in the scope of this study). In summary, control discrepancies that concern irregularities in the vehicle's control system, environmental conditions (e.g., road construction, not visible lane markings), hardware and software disengagements (e.g., system components failure), perception issues (e.g., inappropriate detection of traffic signals, road users, vehicles, and other objects), and planning discrepancies (e.g., irregularities in vehicle's position identification and navigation design) could gravely affect road safety.

Another potential risk that AVs may encounter is cyber-attacks. Cybersecurity is a crucial component for the safe operation of the new technology. Although not much information is still available for the integrity of AVs' safety protocols, the literature has already widely discussed the dangers of remotely controlling the vehicle (Kim, Kim, Jeong, Park, Kim, 2021). Cyber-attacks could have a negative impact on the safety of future road transport systems.

Sharing the road between human-driven vehicles and AVs would indisputably create a complex and demanding situation concerning safety. Today, however, there is a lack of knowledge about their interactions and their implications. Early findings have shown signs of adapted driving behaviour under the presence of the new technology. The most notable example is platooning where driving next to a platoon of AVs resulted in human drivers presenting shorter average and minimum time headways (Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014). These reductions can result in risky situations and can even cause crashes because of the longer reaction times of human drivers compared to AVs. The case of people driving more aggressively or risky toward AVs is another possible scenario (Liu, Du, Wang, & Ju, 2020). It is incontrovertible that aggressive driving behavior can be the leading cause of deteriorating safety on public roads (Ma, Hao, Xiang, & Yan, 2018). In real traffic, aggressive driving is usually expressed as tailgating, performing abrupt and risky lane changes, speeding in heavy traffic, not respecting traffic regulations, etc. (Park, Oh, Kim, Choi, & Park, 2019). Consequently, the potential behavioural adaptation could result in new types of crashes and reduce road safety levels during this disruptive paradigm shift in road networks. Understanding how drivers will interact with AVs is crucial to improving the new technology's development and evaluation.

To summarise, future research should pay more attention to the following areas that could enhance and better indicate the safety implications of higher levels of AVs. More specifically, traffic simulation studies can address identified limitations by calibrating and validating base models based on real-world data. Concerning AVs modelling, sensitivity analysis assessing the impact of fluctuations of parameters on the outputs of the simulations should be included. Researchers could take advantage of the limited AVs road test data to calibrate internal driving behaviour parameters or develop respective control algorithms. Driving simulators could monitor their interactions in controlled environments to account for potential human-drivers behavioural adaptation in mixed traffic conditions. Data could be used to calibrate existing AVs control algorithms further or contribute to new developments that will capture more realistically their driving behaviour. Finally, accident analysis studies should address identified shortcomings and limitations by considering system failure, security risks, and other issues mentioned above to proceed with more accurate estimations.

Following the scoping research methodology applied in our study, we also included evidence not published in peer-review journals. Therefore, the findings should be interpreted with caution, given that our research aims not to assess the quality of the reviewed studies. Furthermore, in line with the scoping review methodology, the study does not include a critical appraisal of the evidence, which is the scope of a systematic review but instead examines emerging and unclear evidence on a specific topic (Munn et al., 2018). Nonetheless, this review offers a comprehensive overview of the state of the literature and has systematically identified the reported AVs' road safety impacts that have been examined to date. This fills an important gap in synthesising the research and provides an evidentiary basis to support further research.

Conclusions

This paper summarises and synthesises the AVs' safety implications as they are reported in the existing literature. In general, this study's results support the conclusion that AVs hold the potential to improve road safety. However, the current review highlights that although automation can improve road safety, the achievable benefits depend on many factors such as the AVs' characteristics and penetration rate, traffic scenarios, and road network characteristics.

Moreover, the findings suggest that a significant amount of real-world driving data is needed to prove the new technology's reliability before its deployment. Real-world data will also enable identifying critical driving situations, allow a more realistic safety assessment, and provide valuable input for traffic simulations to improve driving behaviour models for both AVs and human-driven vehicles, along with other technological developments.

The precondition to obtaining reliable results from traffic simulations should be the appropriate modelling of all road environment aspects (i.e., vehicles, road users, and road geometries) and their interactions and the development of tools or algorithms capable of replicating the decision-making logic of AVs. Additionally, since traffic simulation models enable us to capture the overall traffic flow impacts, having large road networks is essential to evaluate AVs' effects accurately. Their large-scale impact cannot be captured at an intersection level, for instance. Likewise, a wide-ranging traffic scenario (e.g., 24 hours' study instead of only peak hours) will increase critical situations' frequency, reflecting the real-world situation more precisely.

To conclude, it is indisputable that the examined technologies' actual effectiveness will not be known or accurately estimated until sufficient real-world data becomes available. The AVs' impacts are only estimated based on assumptions of effectiveness and enhanced performance compared to human-driven vehicles, which might not be utterly realizable in real-world conditions. Such assumptions would lead to results with high uncertainty and the chance to provide misleading information.

Disclosure Statement

The authors declare that there is no conflict of interest regarding the publication of this article.

References

Analytics, C. (2019). EndNote X9. https://endnote.com/.

Arvin, R., Kamrani, M., Khattak, A. J., & Rios-Torres, J. (2018). *Safety Impacts of Automated Vehicles in Mixed Traffic.* Transportation Research Board 97th Annual Meeting Washington, DC, United States.

Arvin, R., Khattak, A. J., & Rios-Torres, J. (2019). *Evaluating Safety with Automated Vehicles at Signalized Intersections: Application of Adaptive Cruise Control in Mixed Traffic.* Transportation Research Board 98th Annual Meeting, Washington, DC, United States.

Bimbraw, K. (2015). *Autonomous Cars: Past, Present and Future - A Review of the Developments in the Last Century, the Present Scenario and the Expected Future of Autonomous Vehicle Technology*. Paper presented at the Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics.

Boggs, A.M., Arvin, R., & Khattak, A.J. (2020). Exploring the who, what, when, where, and why of automated vehicle disengagements. *Accident Analysis & Prevention. 136*. doi: 10.1016/j.aap.2019.105406

Casualty Acturial Society (2014). Restating the National Highway Transportation Safety Administration's National Motor Vehicle Crash.

Cohen, T., & Cavoli, C. (2018). Automated vehicles: exploring possible consequences of government (non)intervention for congestion and accessibility. *Transport Reviews, 39*(1), pp. 129-151. doi:10.1080/01441647.2018.1524401

Combs, T. S., Sandt, L. S., Clamann, M. P., & McDonald, N. C. (2019). Automated Vehicles and Pedestrian Safety: Exploring the Promise and Limits of Pedestrian

Detection. *American Journal of Preventive Medicine, 56*(1), pp. 1-7. doi:10.1016/j.amepre.2018.06.024

Coppola, P., & Silvestri, F. (2019). Autonomous vehicles and future mobility solutions *Autonomous Vehicles and Future Mobility* (pp. 1-15).

Dean, J., Wray, A. J., Braun, L., Casello, J. M., McCallum, L., & Gower, S. (2019). Holding the keys to health? A scoping study of the population health impacts of automated vehicles. *Bmc Public Health, 19*(1) doi:10.1186/s12889-019-7580-9

Detwiller, M., & Gabler, H. C. (2017). *Potential Reduction in Pedestrian Collisions with an Autonomous Vehicle.* 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Detroit, Michigan, United States.

ETSC. (2001). *Transport Safety Performance Indicators* Brussels: European Transport Safety Council.

Faggela, D. (2020, March 14). *Emerj: The AI Research and Advisory Company*. Retrieved May 15, 2020 from https://emerj.com/ai-adoption-timelines/self-driving-car-timeline-themselves-top-11-automakers/

Fagnant, D., & Kockelman, K. (2014). *Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations.* Transportation Research Board 93rd Annual Meeting, Washington, DC, United States.

Fagnant, D., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. [Article]. *Transportation Research Part a-Policy and Practice, 77*, pp. 167-181. doi:10.1016/j.tra.2015.04.003

Farah, H., Bhusari, S., van Gent, P., Babu, F. A. M., Morsink, P., Happee, R., & van Arem, B. (2020). An Empirical Analysis to Assess the Operational Design Domain of Lane Keeping System Equipped Vehicles Combining Objective and Subjective Risk Measures. *IEEE Transactions on Intelligent Transportation Systems*, pp. 1-10. doi:10.1109/tits.2020.2969928

Farah, H., Erkens, S. M. J. G., Alkim, T., & van Arem, B. (2018). Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions. *Road Vehicle Automation 4*, pp. 187-197. doi:10.1007/978-3-319-60934-8_16

Gandia, R. M., Antonialli, F., Cavazza, B. H., Neto, A. M., Lima, D. A. d., Sugano, J. Y., Nicolai, I., & Zambalde, A. L. (2018). Autonomous vehicles: scientometric and bibliometric review. *Transport Reviews, 39*(1), pp. 9-28. doi:10.1080/01441647.2018.1518937

García, A., & Camacho-Torregrosa, F. J. (2020). Influence of Lane Width on Semi-Autonomous Vehicle Performance. *Transportation Research Record: Journal of the Transportation Research Board, 2674*(9).

Gasser, T. M., & Westhoff, D. (Producer). (2012). BASt-study: Definitions of Automation and Legal Issues in Germany. *Workshop on the Future of Road Vehicle Automation*.

Granados, M. E., Persaud, B., Rajeswaran, T., & Saleem, T. (2018). *Using Microsimulation to Evaluate the Impact of Automated Vehicles on Safety Performance of Signalized Intersections.* Transportation Research Board 97th Annual Meeting, Washington, DC, United States.

Haddaway, N. R., & Bayliss, H. R. (2015). Shades of grey: Two forms of grey literature important for reviews in conservation. *Biological Conservation, 191*, pp. 827-829. doi:10.1016/j.biocon.2015.08.018

Hamed, M. M. (2001). Analysis of pedestrians' behaviour at pedestrian crossings. *Safety Science, 38*(1), pp. 63-82. doi:10.1016/s0925-7535(00)00058-8

Jadaan, K., Al-Braizat, E., Al-Rafayah, S., Gammoh, H., & Abukahlil, Y. (2018). Traffic Safety in Developed and Developing Countries: A Comparative Analysis. *Journal of Traffic and Logistics Engineering*, pp. 1-5. doi:10.18178/jtle.6.1.1-5

Jalali, S., & Wohlin, C. (2012). Systematic Literature Studies: Database Searches vs. Backward Snowballing. *Proceedings of the Acm-Ieee International Symposium on Empirical Software Engineering and Measurement (Esem'12)*, pp. 29-38.

Kakimoto, Y., Iryo-Asano, M., Orhan, E., & Nakamura, H. (2018). A Study on the Impact of AV-HDV Mixed Traffic on Flow Dynamics of Single-Lane Motorway. *Transportation Research Procedia, 34*, pp. 219-226. doi:10.1016/j.trpro.2018.11.035

Kalra, N., & Groves, D. G. (2017). *RAND Model of Automated Vehicle Safety (MAVS): Model Documentation*.

Khoury, J., Amine, K., & Abi Saad, R. (2019). An Initial Investigation of the Effects of a Fully Automated Vehicle Fleet on Geometric Design. *Journal of Advanced Transportation, 2019*, pp. 1-10. doi:10.1155/2019/6126408

Kim, K., Kim, J.S., Jeong, S., Park, J., & Kim, H.K., 2021. Cybersecurity for autonomous vehicles. Review of attacks and defense. *Computers & Security, 103*. doi: 10.1016/j.cose.2020.102150

Kitajima, S., Shimono, K., Tajima, J., Antona-Makoshi, J., & Uchida, N. (2019). Multi-agent traffic simulations to estimate the impact of automated technologies on safety. *Traffic Injury Prevention, 20*, pp. S58-S64. doi:10.1080/15389588.2019.1625335

Kockelman, K., Avery, P., Bansal, P., Boyles, S. D., Bujanovic, P., Choudhary, T., Clements, L., Domenko, G., Fagnant, D., Helsel, J., Hutchinson, R., Levin, M., Li, J., Li, T., Loftus-Otway, L., Nichols, A., Simoni, M., & Stewart, D., (2016). *Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks: A Final Report*.

Kühn, M., & Bende, J. (2020). *Automated cars on motorways: Active and passive safety aspects*. Berlin, Germany: G. T. G. Insurers.

Li, D., & Wagner, P. (2019). Impacts of gradual automated vehicle penetration on motorway operation: a comprehensive evaluation. *European Transport Research Review, 11*(1), pp. 36.

Liljamo, T., Liimatainen, H., & Pollanen, M. (2018). Attitudes and concerns on automated vehicles. *Transportation Research Part F-Traffic Psychology and Behaviour, 59*, pp. 24-44. doi:10.1016/j.trf.2018.08.010

Luttrell, K., Weaver, M., & Harris, M. (2015). The effect of autonomous vehicles on trauma and health care. *Journal of Trauma and Acute Care Surgery, 79*(4), pp. 678-682.

Mahmud, S. M. S., Ferreira, L., Hoque, M. S., & Tavassoli, A. (2019). Micro-simulation modelling for traffic safety: A review and potential application to heterogeneous traffic environment. *IATSS Research, 43*(1), pp. 27-36. doi:10.1016/j.iatssr.2018.07.002

Millonig, A. (2019). Connected and Automated Vehicles: Chances for Elderly Travellers. *Gerontology 65*(5), pp. 571-578. doi: 10.1159/000498908

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., . . . Group, P.-P. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev, 4*, p 1. doi:10.1186/2046-4053-4-1

Morando, M. M., Tian, Q., Truong, L. T., & Vu, H. L. (2018). Studying the Safety Impact of Autonomous Vehicles Using Simulation-Based Surrogate Safety Measures. *Journal of Advanced Transportation*, *2018*(Article ID 6135183), 11p.

Munn, Z., Peters, M. D. J., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Med Res Methodol, 18*(1), p 143. doi:10.1186/s12874-018-0611-x

NHTSA. (2013). *Preliminary Statement of Policy Concerning Automated Vehicles*.

Olia, A., Abdelgawad, H., Abdulhai, B., & Razavi, S. (2016). Assessing the Potential Impacts of Connected Vehicles: Mobility, Environmental, and Safety Perspectives. *Journal of Intelligent Transportation Systems, 20*(5), pp. 485-485. doi:10.1080/15472450.2016.1228375

Ondruš, J., Kolla, E., Vertaľ, P., & Šarić, Ž. (2020). How Do Autonomous Cars Work? *Transportation Research Procedia, 44*, pp. 226-233. doi:10.1016/j.trpro.2020.02.049

Pendleton, S., Andersen, H., Du, X., Shen, X., Meghjani, M., Eng, Y., Rus, D., & Ang, M. (2017). Perception, Planning, Control, and oordination for Autonomous Vehicles. *Machines*, *5*(1). doi: 10.3390/machines5010006

Penmetsa, P., Adanu, E. K., Wood, D., Wang, T., & Jones, S. L. (2019). Perceptions and expectations of autonomous vehicles – A snapshot of vulnerable road user opinion. *Technological Forecasting and Social Change, 143*, pp. 9-13. doi:10.1016/j.techfore.2019.02.010

Pereira, A., Anany, H., Pribyl, O., Prikryl, J., & Ruzicka, J. (2017). Automated Vehicles in Smart Urban Environment: A Review. [Proceedings Paper]. *2017 Smart City Symposium Prague (Scsp)*

Peterson, J., Pearce, P. F., Ferguson, L. A., & Langford, C. A. (2017). Understanding scoping reviews: Definition, purpose, and process. *J Am Assoc Nurse Pract, 29*(1), pp. 12-16. doi:10.1002/2327-6924.12380

Pham, M. T., Rajic, A., Greig, J. D., Sargeant, J. M., Papadopoulos, A., & McEwen, S. A. (2014). A scoping review of scoping reviews: advancing the approach and enhancing the consistency. *Res Synth Methods, 5*(4), pp. 371-385. doi:10.1002/jrsm.1123

Punzo, V., & Ciuffo, B. (2009). How Parameters of Microscopic Traffic Flow Models Relate to Traffic Dynamics in Simulation. *Transportation Research Record: Journal of the Transportation Research Board, 2124*(1), pp. 249-256. doi:10.3141/2124-25

Rau, P., Yanagisawa, M. & Najm, W. G. (2015). *Target Crash Population of Automated Vehicles.* 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Gothenburg , Sweden.

Reddy, N., Farah, H., Huang, Y., Dekker, T., & Van Arem, B. (2020). Operational Design Domain Requirements for Improved Performance of Lane Assistance Systems: A Field Test Study in The Netherlands. *IEEE Open Journal of Intelligent Transportation Systems, 1*, pp. 237-252. doi:10.1109/ojits.2020.3040889

SAE. (2018). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*.

Shladover, S. E. (2018). Connected and automated vehicle systems: Introduction and overview. *Journal of Intelligent Transportation Systems, 22*(3), pp. 190-200. doi:10.1080/15472450.2017.1336053

Singh, S. (2015). *Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey*. National Highway Traffic Safety Administration. Washington, D.C.

Sohrabi, S., Khreis, H., & Lord, D. (2020). Impacts of Autonomous Vehicles on Public Health: A Conceptual Model and Policy Recommendations. Sustainable Cities and Society, 63. doi:10.1016/j.scs.2020.102457

Soteropoulos, A., Berger, M., & Ciari, F. (2018). Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies. *Transport Reviews, 39*(1), pp. 29-49. doi:10.1080/01441647.2018.1523253

Schoenmakers, M., Yang, D., & Farah, H. (2021). Car-following behavioural adaptation when driving next to automated vehicles on a dedicated lane on motorways: A driving simulator study in the Netherlands. Transportation research part F: traffic psychology and behaviour, 78, pp. 119-129. doi: 10.1016/j.trf.2021.01.010

Schwall, M., Tom, D., Trent, V., Favaro, F., & Hohnhold, H. (2020). Waymo Public Road Safety Performance Data. *ArXiv* abs/2011.00038

Taeihagh, A., & Lim, H. S. M. (2019). Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks. *Transport Reviews, 39*(1), pp. 103-128.

Tafidis, P., Pirdavani, A., Brijs, T., & Farah, H. (2019). Can Automated Vehicles Improve Cyclist Safety in Urban Areas? *Safety, 5*(3)doi:10.3390/safety5030057

Thompson, J., Read, G. J. M., Wijnands, J. S., & Salmon, P. M. (2020). The perils of perfect performance; considering the effects of introducing autonomous vehicles on rates of car vs cyclist conflict. *Ergonomics, 63*(8), pp. 981-996. doi:10.1080/00140139.2020.1739326

Tibljas, A. D., Giuffre, T., Surdonja, S., & Trubia, S. (2018). Introduction of Autonomous Vehicles: Roundabouts Design and Safety Performance Evaluation. *Sustainability, 10*(4). doi:10.3390/su10041060

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., . . . Straus, S. E. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Ann Intern Med, 169*(7), pp. 467-473. doi:10.7326/M18-0850

Utriainen, R., & Pollanen, M. (2020). Prioritizing Safety or Traffic Flow? Qualitative Study on Highly Automated Vehicles' Potential to Prevent Pedestrian Crashes with Two Different Ambitions. *Sustainability, 12*(8)doi:10.3390/su12083206

Vanparijs, J., Int Panis, L., Meeusen, R., & de Geus, B. (2015). Exposure measurement in bicycle safety analysis: A review of the literature. *Accident Analysis & Prevention, 84*, pp. 9-19. doi:10.1016/j.aap.2015.08.007

Vasebi, S., & Hayeri, Y. M. (2020). Air emission impacts of low-level automated vehicle technologies in U.S. metropolitan areas. *Transportation Research Interdisciplinary Perspectives, 7*doi:10.1016/j.trip.2020.100194

Wang, L., Fahrenkrog, F., Vogt, T., Jung, O., Kates, R., & National Highway Traffic Safety, A. (2017). *Prospective Safety Assessment of Highly Automated Driving Functions Using Stochastic Traffic Simulation.*

Xie, H., Tanin, E., Karunasekera, S., Qi, J., Zhang, R., Kulik, L., & Ramamohanarao, K. (2019). *Quantifying the Impact of Autonomous Vehicles using Microscopic Simulations.* Proceedings of the 12th ACM SIGSPATIAL International Workshop on Computational Transportation Science.

Yu, H., Tak, S., Park, M., & Yeo, H. (2019). Impact of Autonomous-Vehicle-Only Lanes in Mixed Traffic Conditions. *Transportation Research Record: Journal of the Transportation Research Board*

Zang, S., Ding, M., Smith, D., Tyler, P., Rakotoarivelo, T., & Kaafar, M. A. (2019). The impact of adverse weather conditions on autonomous vehicles: how rain, snow, fog, and hail affect the performance of a self-driving car. *IEEE Vehicular Technology Magazine, 14*(2), pp. 103-111.

Zhu, J., & Krause, S. (2019). *Analysis of the Impact of Automated Lane Changing Behavior on the Capacity and Safety of Merge Segments.* mobil.TUM 2018 "Urban Mobility – Shaping the Future Together" - International Scientific Conference on Mobility and Transport, Munich, Germany.

Zlocki, A., Eckstein, L., & Fahrenkrog, F. (2015). Evaluation and Sign-Off Methodology for Automated Vehicle Systems Based on Relevant Driving Situations. *Transportation Research Record: Journal of the Transportation Research Board*(2489), pp. pp 123–129.

Zlocki, A., Fahrenkrog, F., Benmimoun, M., Josten, J., & Eckstein, L. (2014). Evaluation of Automated Road Vehicles. *Road Vehicle Automation*, pp. 197-208. doi:10.1007/978-3-319-05990-7_17

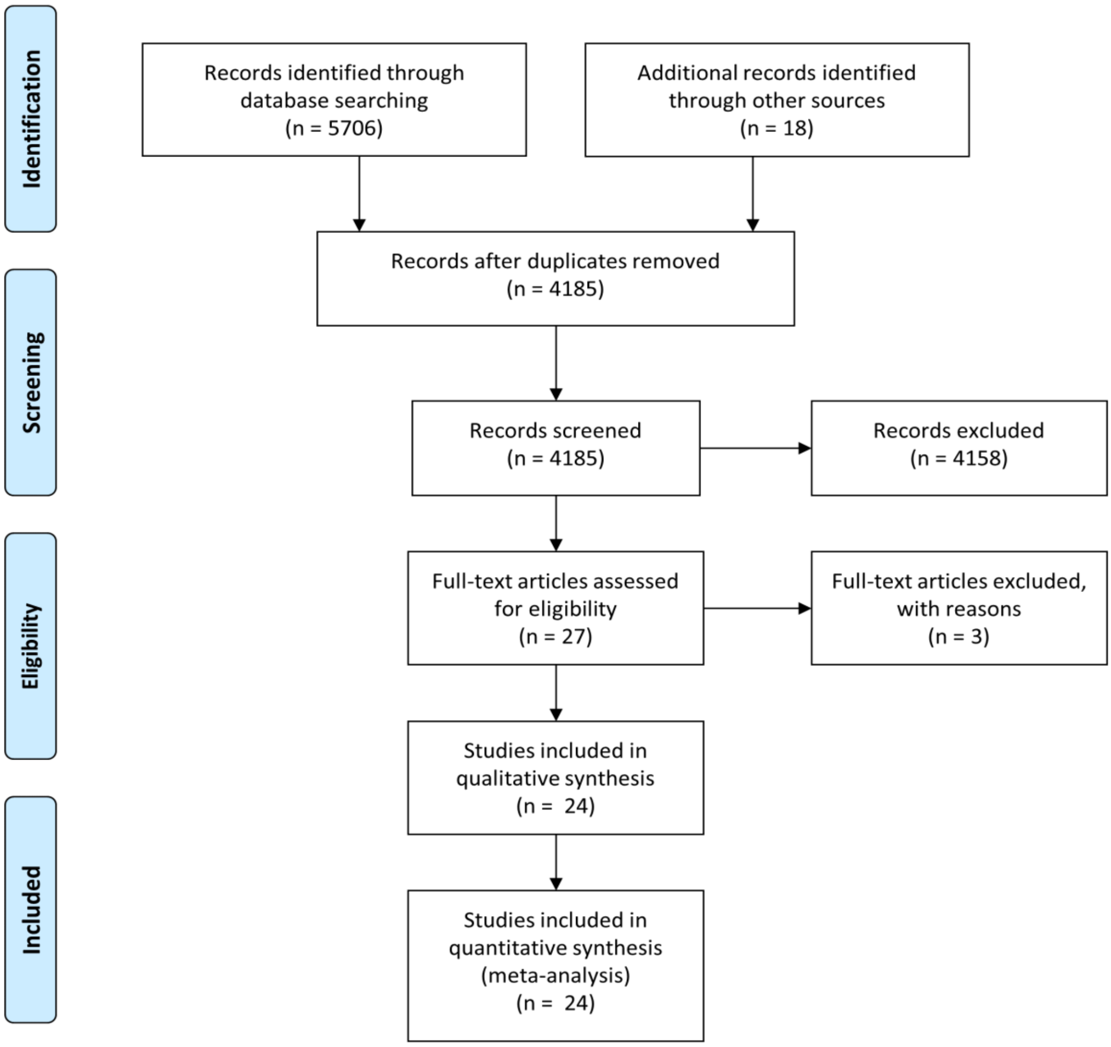

Figure 1. Selection Process Flow Diagram (based on Moher et al., 2015)

Table 1. General Study Characteristics.

ID	Authors, Year	Source		Reference Country
		Academic	Grey Literature	
1	Fagnant and Kockelman, 2014	-	Conference Proceedings	United States
2	Casualty Actuarial Society, 2014	-	Report	United States
3	Rau, Yanagisawa, & Najm, 2015	-	Conference Proceedings	United States
4	Luttrell, Weaver, & Harris, 2015	Peer-Reviewed Article	-	United States
5	Kockelman et al., 2016	-	Report	United States
6	Detwiller and Gabler, 2017	-	Conference Proceedings	United States
7	Kalra and Groves, 2017	-	Report	United States
8	Wang et al., 2017	-	Conference Proceedings	Germany
9	Arvin, Kamrani, Khattak, & Rios-Torres, 2018	-	Conference Proceedings	United States
10	Granados, Persaud, Rajeswaran, & Saleem, 2018	-	Conference Proceedings	Canada and United States
11	Kakimoto, Iryo-Asano, Orhan, & Nakamura, 2018	-	Conference Proceedings	Japan
12	Morando, Tian, Truong, & Vu, 2018	Peer-Reviewed Article	-	Australia and Singapore
13	Tibljas, Giuffre, Surdonja, & Trubia, 2018	Peer-Reviewed Article	-	Croatia and Italy
14	Arvin, Khattak, & Rios-Torres, 2019	-	Conference Proceedings	United States
15	Combs, Sandt, Clamann, & McDonald, 2019	Peer-Reviewed Article	-	United States
16	Kitajima, Shimono, Tajima, Antona-Makoshi, & Uchida, 2019	Peer-Reviewed Article	-	Japan

ID	Authors, Year	Source		Reference Country
		Academic	Grey Literature	
17	Li and Wagner, 2019	Peer-Reviewed Article	-	China and Germany
18	Tafidis, Pirdavani, Brijs, & Farah, 2019	Peer-Reviewed Article	-	Belgium and The Netherlands
19	Xie et al., 2019	-	Conference Proceedings	Australia
20	Yu, Tak, Park, & Yeo, 2019	Peer-Reviewed Article	-	Republic of Korea
21	Zhu and Krause, 2019	-	Conference Proceedings	Germany
22	Kühn and Bende, 2020	-	Report	Germany
23	Thompson, Read, Wijnands, & Salmon, 2020	Peer-Reviewed Article	-	Australia
24	Utriainen and Pollanen, 2020	Peer-Reviewed Article	-	Finland

Table 2. Study Design

ID	Methodological Approach	Scale of Application	Mobility Concept	Traffic Conditions	Type/ Level of AVs[1]	Penetration Rate
1	Accident Analysis	National Network	Vehicles Cyclists Pedestrians	-	Level 5 AVs - SAVs[2]	10%, 50%, and 90% (10% SAVs)
2	Accident Analysis	National Network	-	-	Level 5 AVs	100%
3	Accident Analysis	National Network	Vehicles Cyclists Pedestrians	-	Level 4 & 5 AVs	100%
4	Accident Analysis	National Network	Vehicles Cyclists Pedestrians	-	Level 5 AVs & SAVs	10%, 50%, and 90% (10% SAVs)
5	Traffic Simulation	Urban and Sub-urban Intersections and Urban and Rural Road Segments	Cars	Low, Medium, and High Flow (depends on the case study)	Level 4 & 5 AVs	From 25% to 100% in steps of 25%
6	Accident Analysis	Urban Road Networks	Vehicles Pedestrians	-	Level 5 AVs	100%
7	Accident Prediction Model	National Network	Cars	-	Level 4 & 5 AVs	0.01% to 99/99%
8	Traffic Simulation	Rural Road Segments	Cars	Low and High Flow	Level 5 AVs	-
9	Traffic Simulation	Sub-urban Intersection	Cars	Average Annual Daily Traffic (AADT)	Level 5 AVs	2%, 5%, 15%, 20%, 30%, 50%, 70%, 90% and 100%

[1] For the purpose of our study if the type or level of AV is not clearly stated or is described in a different taxonomy, we defined it based on its adopted capabilities.

[2] Shared Automated Vehicles

ID	Methodological Approach	Scale of Application	Mobility Concept	Traffic Conditions	Type/ Level of AVs[1]	Penetration Rate
10	Traffic Simulation	Urban Intersections	Vehicles	Average Annual Daily Traffic	Level 4 & 5 AVs	50% and 100%
11	Traffic Simulation	Rural Road Segment	Cars	-	Level 4 & 5 AVs	From 10% to 100% in steps of 10%
12	Traffic Simulation	Sub-urban Intersection and Roundabout	Vehicles	-	Level 4 AVs	From 25% to 100% in steps of 25%
13	Traffic Simulation	Sub-urban Roundabouts	Cars	High Flow	Level 4 & 5 AVs	10%, 25% and 50%
14	Traffic Simulation	Sub-urban Intersection	Cars	-	Level 4 & 5 AVs	2%, 5%, 15%, 20%, 30%, 50%, 70%, 90% and 100%
15	Accident Analysis	National Network	Vehicles Pedestrians	-	Level 5 AVs	100%
16	Traffic Simulation	Urban Road Network	Cars Pedestrians	Average Annual Daily Traffic	Level 4 AVs	25% and 75%
17	Traffic Simulation	Rural Road Segment	Cars	Low, Medium and High Flow	Level 4 & 5 AVs	10%, 30%, 50%, 70%, 90% and 100%
18	Traffic Simulation	Urban Road Network	Cars Cyclists	High Flow	Level 4 & 5 AVs	100%
19	Traffic Simulation	Urban Road Networks	Cars Pedestrians	Low, Medium, and High Flow	Level 4 AVs	From 20% to 100% in steps of 20%
20	Traffic Simulation	Rural Road Segment	Cars	High Flow	Level 4 & 5 AVs	From 20% to 100% in steps of 20%

ID	Methodological Approach	Scale of Application	Mobility Concept	Traffic Conditions	Type/ Level of AVs[1]	Penetration Rate
21	Traffic Simulation	Road[3] Segment	Cars	Low and High Flow	Level 4 & 5 AVs	-
22	Accident Analysis	National Network	Vehicles Cyclists Pedestrians	-	Level 4 & 5 AVs	100%
23	Traffic Simulation	Urban Road Network	Cars Cyclists	-	Level 4 & 5 AVs	20%, 0.01% to 100%
24	Accident Analysis	National Network	Cars Pedestrians	-	Level 4 & 5 AVs	100%

[3] Not enough information is available to define the environment of the road segment.

Table 3. Study Findings.

ID	Metrics	Safety Implications - Findings		
		Positive	**Negative**	**Neutral/Other**
1	Crash Cost Savings	Reduction of crash costs	-	-
2	Number of preventable accidents	Increase the number of preventable accidents	-	In many cases, AVs effectiveness can be eliminated or reduced due to various factors
3	Target crash population	Potential to address the great majority of crashes	-	-
4	Number of crashes	Reduction of crashes	-	-
5	Number and severity of conflicts based on SSM[4]	Decrease the number and severity of conflicts (general trend)	Increase the number of conflicts at low rates in some cases	-
6	Number of pedestrians collisions	Decrease the number of pedestrian collisions	-	AVs even in ideal conditions unable to prevent all the collisions
7	Relative fatality rate as a function of cumulative miles driven by HAVs and number of annual fatalities	Decrease the number of annual fatalities and relative fatality rates	-	-
8	Survival (crash-free) probability	AVs have less probability of having an accident	-	-
9	The average number of crashes	Decrease the average number of crashes	Increase the average number of crashes at low rates in some cases	-

[4] surrogate safety measures

ID	Metrics	Safety Implications - Findings		
		Positive	**Negative**	**Neutral/Other**
10	The annual number of crashes, number of conflicts based on SSM and crash modification factors	Decrease the total number of crashes based on the total number of conflicts	-	Present smaller safety benefits in case of potential safety treatments
11	SSM	Safety can be improved	-	-
12	Number of conflicts based on SSM	Decrease the total number of conflicts	Increase the total number of conflicts at low rates in some cases	-
13	The annual number of crashes, number of conflicts based on SSM	-	Increase the total number of conflicts	-
14	Number of conflicts based on SSM	Decrease the average number of conflicts	-	-
15	Number of preventable fatalities	Decrease the number of preventable fatalities	-	-
16	Number of total crashes, crash rates by distance driven, average relative crash rates, average crash speed, relative crash speed, estimated fatalities	Decrease the total number of crashes, average crash speed, and estimated fatalities (severity)	Increase the total number of crashes attributed to human-driven vehicles	-
17	SSM	Decrease the number of Time-to-Collision (TTC) events	There is a negative impact at low rates in some cases	Negative impact at low rates can be mitigated by Variable Speed Limit (VSL)

ID	Metrics	Safety Implications - Findings		
		Positive	Negative	Neutral/Other
18	Total number and severity of conflicts based on SSM	Decrease the total number and severity of conflicts	-	-
19	SSM	Decrease the rate of TTC events	Increase the rate of TTC events in some cases	-
20	Average collision risk based on SSM	-	-	The safety was either improved or worsened depending on the rates
21	Number of severe conflicts based on SSM	Decrease the number of severe conflicts	-	-
22	Safety benefits [%] in terms of avoidable accidents	Increase the % of avoidable accidents	-	-
23	Mean Number of Conflicts	Decrease the overall conflicts	The mean number of conflicts between human-driven cars and cyclists increased	-
24	Number of Preventable Crashes	Increase the number of preventable crashes.	-	Not all crashes can be prevented. Prioritising traffic flow over safety reduces the number of preventable crashes.

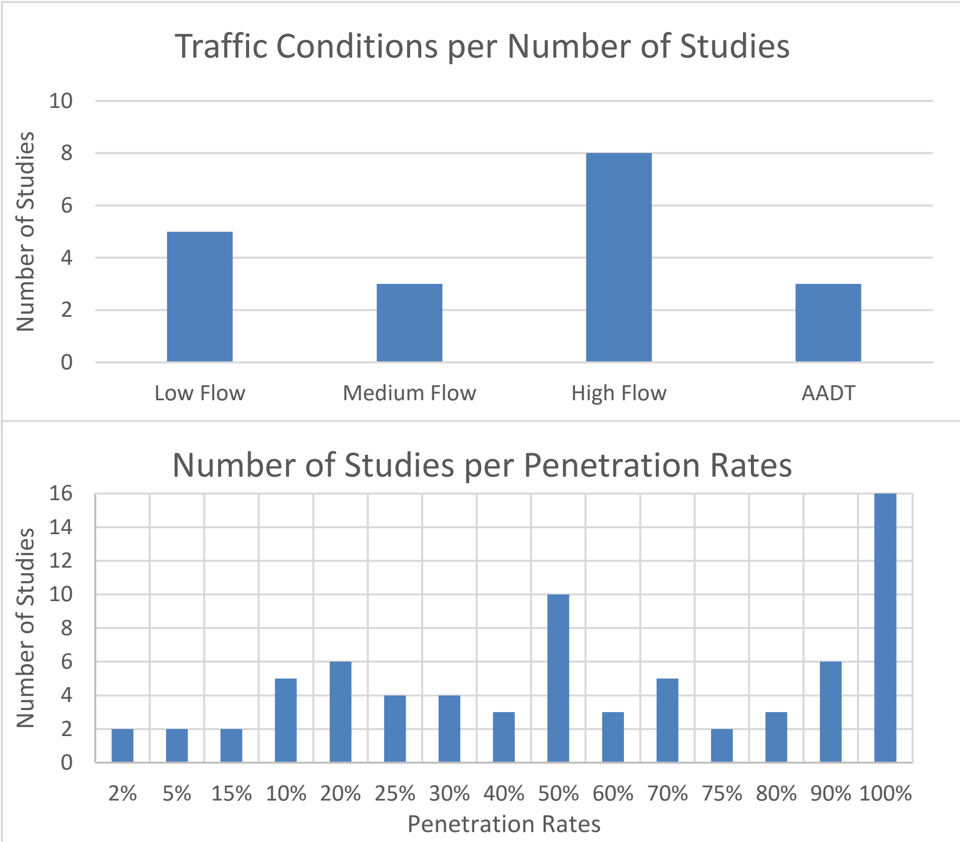

Figure 2. Study Designs' Main Characteristics

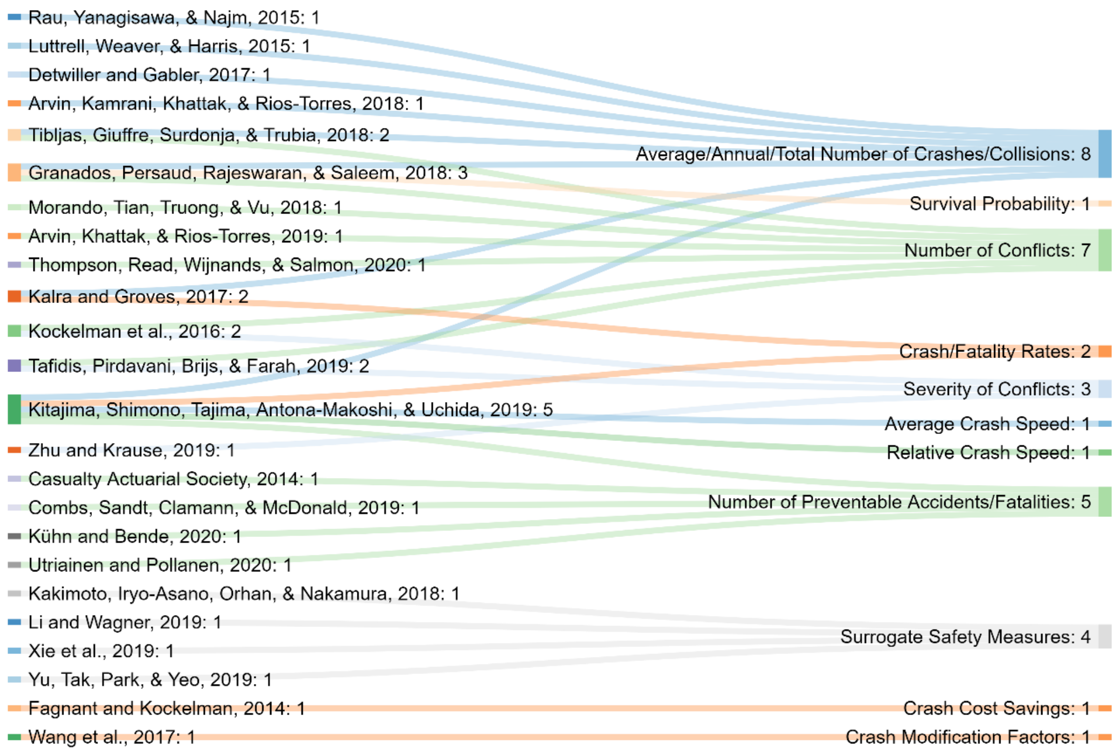

Figure 3. Adopted Metrics per Study