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DOCTORAL DISSERTATION

The effects in distance and time of traffic calming measures near road transitions and discontinuities by means of driving simulator research

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Oral defence

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ABBREVIATIONS

Acc/dec	Longitudinal acceleration and deceleration
ANOVA	Analysis of Variance
DIB	Digital illuminated billboards
DID	Digital information displays
ERC	Essential Recognizable Characteristics
GDP	Gross domestic product
HP	Herringbone pattern
IMOB	Instituut voor Mobiliteit / Transportation Research Institute
ISA	intelligent speed adaption
kph	Kilometer per hour
LP	Lateral position
LTM	Long-term memory
m	Meter
MANOVA	Multivariate analysis of variance
OECD	Organisation for Economic Co-operation and Development
PDT	Peripheral Detection Task
s	Second
SA	Situation awareness
SDLP	Standard deviation of lateral position
SER	Self-explaining roads
STM	Short-term memory
STSS	Short-term sensory stage
TCM	Traffic calming measures
TRS	Transversal rumble strips
v	Speed
VMAE	Visual motion after-effect

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- Mama en papa: "Waarom heb je je kamer nog niet opgeruimd?"
- Ik: "Om daarom."

En daar sta je dan als ouder. Mijn ouders vonden er niets beter op om vanaf dan consequent de volgende zin te gebruiken: "*Om daarom* is geen antwoord". Zij en ik hadden echter nooit gedacht dat dit zulke verstrekkende gevolgen zou hebben. Want wil je tegenwoordig weten hoe iets werkt dan is het antwoord niet "Om daarom". Nee, je moet er papers over schrijven met tal van referenties, wat dan leidt tot een doctoraat van 260 pagina's. Dus bedankt mama en papa om me nieuwsgierig te maken om uit te zoeken hoe alles in elkaar zit, me kritisch te leren denken, me alle kansen te geven om mezelf hierin te ontwikkelen en ontdekken en me hierin onvoorwaardelijk te steunen.

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SUMMARY

Road safety is worldwide a serious problem which leads to high physical, psychological, material and economic costs. The pro-active character of the **Safe System Approach** (paragraph 1.3) provides a good starting-point to achieve the joint target to drastically reduce road fatalities and accidents. The road safety measures in the context of the Safe System Approach take humans' limitations with respect to information processing capabilities and human's body tolerance into account. The, so called, ergonomic or human-centered road design incorporates human factors during the whole design process of the road and the road environment in order to avoid road accidents and minimize the accident severity.

The design of a predictable and recognizable environment enables road users to call the right expectations. This encourages the desired behavior in a given environment, and makes it easier for road users to predict the behavior of other road users, thereby supporting road safety. Several studies indicate the importance of recognizable transitions (i.e., between two road categories) and discontinuities (i.e., major change in road design within the same road category) as an adaptation of the behavior of the driver is required at these locations. Typically, transitions and discontinuities go together with an important change in speed management and/or attention level in order to maintain safe driving behavior. Nevertheless, research and design standards are rather scarce in this domain. Based on the literature, it can be concluded that additional insight in the design and influence of transitions and discontinuities is required.

This thesis focusses specifically on traffic calming measures (TCM) located nearby rural-to-urban transitions and tangent-to-curve discontinuities. Both mental underload and an excessive and/or inadequate driving speed can cause unsafe situations. The general objective of this thesis is **to examine the effects in distance (along the road) and time (under repeated exposure during 5 consecutive days) of traffic calming measures near road transitions and discontinuities**. In total, five driving simulator studies were performed in order to investigate the following main research questions:

1. Can we obtain a desired behavioral adaptation contributive to road safety in distance (along the road) by means of traffic calming measures?
2. With respect to distance along the road: Is there a difference between the different traffic calming measures in terms of the extent to which they contribute to a desired behavioral adaptation supporting road safety?
3. With respect to time (i.e., under repeated exposure during 5 consecutive days): Does the repeated exposure to the traffic calming measures have an influence on driving behavior near transitions or discontinuities?

Driving simulator research is considered as a suitable research tool in human-centered road design and can provide researchers with total control over the various driving conditions that matter and the environmental conditions. In addition, simulator experiments are safe and cost efficient and a variety of driving performance data can be collected at a continuous high rate in order to evaluate new (technological) developments. The driving simulator of the Transportation Research Institute – Hasselt University (Belgium) was used in all the five experiments. The medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated) is a fixed-base driving simulator and the visual virtual environment is presented on a large 180° field of view seamless curved screen.

By investigating both the longitudinal and lateral dimensions of driving behavior, this thesis will come to a multidimensional evaluation of different TCM. Chapter 2 describes some **methodological foundations related to driving simulator research**. More specifically, the suitability of different driving simulator sampling approaches, which is to be carried out prior to statistical analysis, is elaborated. The analysis of different driving simulator datasets shows that a point location based analysis (e.g., speed at curve entry, curve middle, and curve exit) requires another data sampling approach compared to a zonal-based analysis (e.g., mean speed in a zone of 50 m nearby an intersection). Furthermore, an interpolation technique and alternative formulas are preferred over using raw sampled data to calculate mean parameter values. Based on this research (paragraph 2.4), we would like to demonstrate that it is very important to mention the data processing approach in the driving simulator methodology. In the driving simulator studies performed in this thesis (except study 3.1) we used the interpolation technique to prepare the simulator data before the statistical analysis took place.

In Chapter 3 we focus on the **transition between rural and urban areas**. From the perspective of road safety engineering, a speed reduction is often implemented within the transition zone to urban areas serving not only a residential function, but also a traffic function (i.e., allowing the traffic to drive through). But in many situations speed limits on rural roads are higher than in the urban area, and drivers have experienced a sustained period of driving at higher speed before accessing an urban area. Previous studies (Elliot, McColl, & Kennedy, 2003; Martens, Comte, & Kaptein, 1997) have shown that this can lead to detrimental effects leading to reduced cognitive arousal and workload and the risk of underestimating the actual travel speed.

Two driving simulator studies (paragraph 3.1 and 3.2) investigating the influence of a **gate construction**, located at the entrance between a rural and urban area, show a significant speed reduction between -1.2 and -4.0 kph. The longitudinal analysis shows that this speed reduction effect sustained during the five successive days of the research. Although a significant speed reduction is found, the effect is limited to the direct vicinity of the gate (i.e., from 200 m before until 100 m after the entrance). Even though participants are inclined to accelerate again once passed by this gate, they always keep driving at an appropriate speed, i.e., close to the speed limit of 50 kph. Furthermore, drivers perform this speed reduction rather smoothly as the standard deviation of acceleration/deceleration is only slightly influenced by the presence of the gate. Besides the longitudinal control, managing the vehicle's horizontal position within the driving lane is also an important factor in road safety. The cross-sectional experiment reveals a higher standard deviation of lateral position within the direct vicinity of the gate construction (i.e., between 97 m before and 97 m after the entrance). This effect however is not present in the longitudinal experiment.

During a third driving simulator experiment (paragraph 3.3) participants are exposed to three different messages on a **digital information display** (DID) which is located after the rural-to-urban transition. Although the results are not exactly the same at both locations under investigation, the "Speed enforcement" message is most effective in reducing the driving speed (i.e., -2.0 to -3.2 kph from 25 m before until 175 m after the DID), followed by the "Too fast" message (-2.3 to -3.1 kph from 25 m before to 100 m after the DID) and the Smiley logo (-1.9 to -2.8 kph from 50 m before until 75 m after the DID) compared to the baseline condition. This implies that a deterrence strategy, where drivers are confronted with the (financial) risk of receiving a fine, is more effective in reducing speed compared to the social approval / disapproval messages. In addition, the post-experiment survey shows that messages indicating a speed enforcement or a fine are considered by participants as the most effective. With respect to mean acceleration/deceleration, the strongest deceleration maneuver is established during the last 50 m before the DID and is lower than the recommended value of -0.85 m/s² (Lamm & Choueiri, 1987) to obtain a safe traffic. Too high deceleration rates can lead to rear-end collisions and disturbances in the traffic flow.

Chapter 4 focusses on the **discontinuity between long tangents and dangerous curves**. Curves typically are associated with an increased safety risk: accident rates are 1.5 to 4 times higher than in tangents (i.e. straight road sections) and 25 to 30% of all fatal accidents occur in curves (Safetynet, 2009a; Srinivasa et al., 2009). Charlton (2007) proposed three main causative factors for accidents in curves, i.e., inappropriate speed monitoring, failure to maintain proper lateral position, and inability to meet increased attentional demands. Extensive experimental research on human factors and road design determined that these behavioral problems often relate to the geometric properties of curves. Unfortunately, these geometric design properties are hard to change on the short term with a limited budget.

The fourth driving simulator study (paragraph 4.1) compares two perceptual pavement markings, i.e., transversal rumble strips (TRS) located at the tangent before the curve and herringbone pattern (HP) located along the curve. Two real-world curves with strong indications of a safety problem are replicated as realistic as possible in the simulator. The driving simulator experiment shows that the

herringbone pattern (HP) reduces driving speed from the curve entry until the curve end between -2.2 and -3.5 kph compared to the baseline condition. The maximum deceleration is located at 50 m before the curve. The **transversal rumble strips** (TRS) are the most effective on the tangent and the resulting lower driving speed gives participants more time to obtain the right expectation about the upcoming curve. At location A speed reductions between -8.9 and -9.8 kph are measured between 166 and 50 m before the curve in the cross-sectional experiment. A speed reduction between -4.7 and -5.9 kph remains during the experimental period of the five days in the longitudinal study (paragraph 4.2). The TRS result in speed reductions between -2.3 and -5.3 kph between 166 m before the curve and the curve middle at location B. Speed reductions between -1.0 and -2.6 kph are measured between 166 m before the curve and the curve entry under repeated exposure. Although these speed reductions are often larger than the speed reductions induced by the HP, the deceleration maneuver is smoother compared to the baseline condition and started already at 166 m before the curve. Furthermore, the influence of the TRS and HP on the mean lateral position is rather limited.

Based on the results of the different driving simulator experiments, several **recommendations** are discussed in Chapter 5. These recommendations can support road agencies and road designers to make their design safer. The fact that the various TCMs, studied apart and at specific transitions and discontinuities, result in speed reductions which are limited to the direct vicinity of the TCM has some implication on the design. At a macro level we advise policy makers to always carefully consider the broader situational context (such as whether the road serves a traffic- rather than a residential function) before applying a TCM and to make a good selection of potential dangerous transitions and discontinuities to avoid excessive implementation of the TCM. At a meso level, the combination of several TCMs along the road might help to further extend the speed reduction effect triggered by a previous TCM. For example, the combination of a gate construction with a DID might for instance increase the effectiveness of the whole TCM scheme. The visual link between a TCM and the potential dangerous situation or location is in general important in order to improve a feeling of credible speed management and to avoid compensating behavior (i.e., accelerating immediately after the TCM) or reducing effectiveness in time. At a micro level, we advise road designers to take the concept of *forgiving roads* into account where the road environment ensures that the consequences of an error are reduced to a minimum. According to the literature, obstacle-free zones and collision-friendly obstacle protections are important design examples.

Furthermore, the **application of driving simulator research in geometric road design** is discussed. Driving simulator research is considered as a suitable research tool in human-centered road design. However, some important issues which were faced with during the different driving simulator experiments are described. Furthermore, the role of driving simulator research is described within a general evaluation process which can be applied to estimate the potential safety effects of geometric road design in a proactive way.

Finally, some **ideas for future research** are described. Besides the different TCMs examined in this thesis, a variety of other different geometric design configurations exist. Future research could focus on such different configurations, try to determine the optimal location of the TCM with respect to the transition or discontinuity (e.g., what is the optimal distance between the TRS and the curve entry), the optimal distance between the markings in the TRS or HP configuration or to investigate the influence of complementary TCMs along the thoroughfare or curve. Finally, a suggestion is made to improve a systematic approach to include results of local or international research in design manuals, handbooks and circulars.

SAMENVATTING

Verkeersonveiligheid is wereldwijd een groot probleem dat leidt tot hoge lichamelijke, psychische, materiële en economische kosten. Het proactieve karakter van de **Safe System Aanpak** vormt een goed uitgangspunt om het aantal ongevallen en slachtoffers drastisch te laten reduceren. De verkeersveiligheidsmaatregelen in de context van de Safe System Aanpak houden rekening met de beperkingen van de informatieverwerking en de fysieke kwetsbaarheid van de weggebruiker. Bij een ergonomisch of *human-centered* wegontwerp worden deze menselijke factoren tijdens het gehele ontwerpproces van de weg en de wegomgeving in rekening genomen met als doel om ongevallen te vermijden en de ernst ervan te minimaliseren.

Een voorspelbare en herkenbare wegomgeving wekt idealiter de juiste verwachtingen op bij de weggebruiker. Het moedigt het gewenste gedrag aan in een bepaalde omgeving en vergemakkelijkt de voorspelbaarheid van het gedrag van de andere weggebruikers. Hierdoor wordt de verkeersveiligheid bevorderd. Verschillende studies tonen het belang van herkenbare transities (i.e., tussen twee wegcategorieën) en discontinuïteiten (i.e., belangrijke verandering in wegontwerp binnen eenzelfde categorie) aan. Deze transities en discontinuïteiten vragen namelijk een gedragsverandering zoals een belangrijke snelheidsverandering en/of een aanpassing van het aandachtsniveau om een veilig rijgedrag te bekomen. Ondanks het belang van een herkenbaar ontwerp blijken onderzoek en ontwerpstandaarden eerder beperkt. Op basis van de literatuur kan er daarom geconcludeerd worden dat bijkomend inzicht in het ontwerp en de invloed van transities en discontinuïteiten wenselijk is.

Deze thesis focust specifiek op snelheidsremmende maatregelen die gelokaliseerd zijn bij transities van een landelijke naar een stedelijke omgeving en discontinuïteiten tussen een lange rechte weg (tangent) en een gevaarlijke bocht. Zowel mentale onder- en overbelasting en overdreven en/of onaangepaste snelheid kunnen onveilige situaties veroorzaken. De algemene doelstelling van deze thesis is **het onderzoeken van de effecten in afstand (over het onderzochte wegsegment) en in tijd (met herhaalde blootstelling gedurende 5 opeenvolgende dagen) van snelheidsremmende maatregelen bij transities en discontinuïteiten**. In totaal werden vijf rijsimulatorstudies uitgevoerd om drie onderzoeksvragen te onderzoeken:

1. Kan er met behulp van snelheidsremmende maatregelen een gedragsverandering bekomen worden over een afstand (over het onderzochte segment) die bijdraagt aan de verkeersveiligheid?
2. Met betrekking tot afstand over het onderzochte wegsegment: Is er een verschil tussen de verschillende snelheidsremmende maatregelen in de

mate waarin ze bijdragen aan een gedragsverandering die bijdraagt aan de verkeersveiligheid?
3. Met betrekking tot tijd (i.e., met herhaalde blootstelling gedurende 5 opeenvolgende dagen): Heeft een herhaalde blootstelling aan de snelheidsremmende maatregelen een invloed op rijgedrag bij transities en discontinuïteiten?

Rijsimulatoronderzoek wordt beschouwd als een geschikte onderzoekstool in ergonomisch wegontwerp en kan onderzoekers volledige controle bieden over tal van rijcondities en omgevingsfactoren. Daarnaast zijn rijsimulatorstudies veilig en kostenefficiënt en kan er een grote variatie aan data over het rijgedrag verzameld worden om nieuwe (technologische) ontwikkelingen uit te testen. De rijsimulator van het Instituut voor Mobiliteit – Universiteit Hasselt (België) werd gebruikt in de vijf experimenten. Deze rijsimulator (STISIM M400; Systems Technology Incorporated) is een rijsimulator met een vaste (niet-bewegende) stuurunit en een 180° naadloos scherm waarop het scenario geprojecteerd wordt.

De verschillende snelheidsremmende maatregelen worden multidimensionaal geëvalueerd. Er wordt dus zowel naar de longitudinale als de laterale dimensie van het rijgedrag gekeken. In Hoofdstuk 2 wordt dieper ingegaan op een aantal **methodologische aspecten van rijsimulatoronderzoek**. De geschiktheid van verschillende methodes voor datalogging en –verwerking, die plaatsvinden voor de statistische analyses, worden onderzocht. De analyse van data op een puntlocatie (vb. snelheid bij begin, midden of einde van een bocht) vereist namelijk een andere aanpak dan in een zone (vb. gemiddelde snelheid in een 50m zone bij een kruispunt). Er wordt tot slot aanbevolen om gebruik te maken van een interpolatietechniek om gemiddelde parameterwaardes te berekenen in plaats van dit te baseren op ruwe simulatordata. In de rijsimulatorstudies in deze thesis (met uitzondering in studie 3.1) gebruikten we steeds de interpolatietechniek om de rijsimulatordata voor te bereiden op de statistische analyses.

In Hoofdstuk 3 wordt er gefocust op de **transitie tussen een landelijk en stedelijke omgeving**. Deze transitie gaat vaak samen met een snelheidsreductie in de transitiezone naar de stedelijke omgeving. Naast de verblijfsfunctie is de verkeersfunctie in deze stedelijke omgeving ook belangrijk. Bestuurders die in de landelijke omgeving gedurende een langere tijd aan een hogere snelheid gereden hebben, kunnen bij het binnenrijden van de stedelijke omgeving een mentale onderbelasting ondervinden en lopen het risico om hun snelheid te onderschatten.

Twee rijsimulatorstudies (paragraaf 3.1 en 3.2) onderzoeken het effect van een **poortconstructie** die gelokaliseerd is aan de overgang van buiten naar binnen de bebouwde kom en stellen snelheidsreducties tussen -1.2 en -4.0 km/u vast. De longitudinale analyses tonen aan dat dit snelheidsverlagende effect behouden blijft tijdens het vijf dagen durende onderzoek. Het effect van de snelheidsreductie is echter beperkt tot de directe omgeving van de poortconstructie (van 200 m voor tot 100 m na de transitie). Ondanks dat bestuurders geneigd zijn om opnieuw te versnellen nadat ze de poort gepasseerd zijn, houden ze een gepaste snelheid aan (dicht bij de snelheidslimiet van 50 km/u). Omdat de standaardafwijking van de acceleratie/deceleratie slechts zeer beperkt beïnvloed wordt door de poort, kan er geconcludeerd worden dat de snelheidsreductie vlot en zacht verloopt. Naast de longitudinale controle is het managen van de horizontale positie van het voertuig binnen de rijstrook ook belangrijk voor de verkeersveiligheid. Het cross-sectionele experiment toont een hogere standaardafwijking van de laterale positie in de directe omgeving van de poort (tussen 97 m voor en 97 m na de transitie). Dit effect is echter niet aanwezig in het longitudinale experiment.

In een derde rijsimulatorexperiment (paragraaf 3.3) worden deelnemers blootgesteld aan drie verschillende boodschappen op een digitaal informatie paneel (DIP) dat gelokaliseerd is na de overgang van buiten naar binnen de bebouwde kom. Ondanks dat de resultaten niet identiek zijn op beide onderzoekslocaties, is de boodschap "Flitscontrole" het meest effectief in het reduceren van de snelheid (-2.0 tot -3.2 km/u tussen 25 m voor en 175 m na het DIP), gevolgd door de "Te snel" boodschap (-2.3 tot -3.1 km/u tussen 25 m voor en 100 m na het DIP) en het Smiley logo (-1.9 tot -2.8 km/u tussen 50 m voor en 75 m na het DIP) in vergelijking met de controleconditie. Dit toont aan dat een afschrikkende (*deterrence*) aanpak, waarbij bestuurders geconfronteerd worden met het (financiële) risico om een boete te krijgen, effectiever is in het verlagen van de snelheid in vergelijking met de sociale goed-/afkeurende boodschappen. Daarnaast schatten deelnemers in een postbevraging in dat boodschappen gerelateerd aan een snelheidscontrole of een boete effectiever zijn. De grootste snelheidsreductie vindt plaats tijdens de laatste 50 m voor het DIP en is lager dan de aanbevolen waarde van -0.85 m/s² (Lamm & Choueiri, 1987) voor veilig verkeer. Een te sterk afremmaneuver kan namelijk leiden tot kop-staart aanrijding en een onstabiele verkeersstroom.

Hoofdstuk 4 focust op de **discontinuïteit tussen lange rechte wegen (tangent) en gevaarlijke bochten**. Bochten worden typisch geassocieerd met een verhoogd veiligheidsrisico: het ongevalsrisico ligt 1.5 tot 4 keer hoger in bochten in vergelijk met rechte wegen en 25 tot 30% van alle dodelijke ongevallen gebeurt in bochten (Safetynet, 2009a; Srinivasa et al., 2009). Charlton (2007) stelt dat er drie belangrijke ongevalsfactoren zijn voor bochten: naast een onaangepaste snelheid en aandachtsallocatie speelt ook de suboptimale laterale wegpositie een rol. Uitgebreid experimenteel onderzoek met betrekking tot wegontwerp en menselijke factoren toont aan dat gedragsproblemen vaak gerelateerd zijn aan de geometrische eigenschappen van bochten. Deze geometrische eigenschappen zijn echter op korte termijn moeilijk te wijzigen met een beperkt budget.

Het vierde rijsimulatorexperiment (paragraaf 4.1) vergelijkt twee perceptuele wegmarkeringen, nl. transversale rammelstroken (*transversal rumble strips*) (TRS) die gelokaliseerd zijn op de tangent voor de bocht en een visgraatpatroon (*herringbone pattern*) (HP) dat doorheen de bocht wordt aangelegd. Twee bochten die in de werkelijkheid sterke indicaties van een verkeersveiligheidsprobleem hebben, worden zo exact mogelijk nagebouwd in de rijsimulator. Het rijstimulatorexperiment toont aan dat het **visgraatpatroon (*herringbone pattern*)** (HP) de snelheid reduceert vanaf het begin tot het einde van de bocht tussen -2.2 en -3.5 km/u in vergelijking met de controleconditie. De maximale deceleratie is gelokaliseerd op 50 m voor de bocht. De **transversale rammelstroken** (TRS) zijn het meest effectief op de tangent en de bijhorende snelheidsreductie geven bestuurders meer tijd om de juiste verwachtingen op te wekken tijdens het naderen van de bocht. In het cross-sectionele experiment zijn op locatie A snelheidsreducties tussen -8.9 en -9.8 km/u gemeten tussen 166 en 50 m voor de bocht. In de longitudinale studie wordt een snelheidsreductie tussen -4.7 en -5.9 km/u gemeten (paragraaf 4.2). Op locatie B worden snelheidsreducties tussen -2.3 en -5.3 km/u gemeten tussen 166 m voor de bocht en het midden van de bocht. Bij een herhaalde blootstelling daalt de snelheid tussen -1.0 en -2.6 km/u tussen 166 m voor de bocht en het begin van de bocht. Ondanks dat de snelheidsreducties over het algemeen groter zijn dan bij het HP, verloopt de deceleratie zachter dan in de controleconditie en start deze al op 166 m voor de bocht. Tot slot is de invloed van beide markering op de laterale controle eerder beperkt.

Op basis van de resultaten van de verschillende rijsimulatorstudies worden enkele **aanbevelingen** besproken in Hoofdstuk 5. Deze aanbevelingen kunnen agentschappen verantwoordelijk voor wegen en verkeer en wegontwerpers ondersteunen in hun ontwerp en bij hun 'gedeelde verantwoordelijkheid' binnen de Safe System Aanpak. Het feit dat de verschillende snelheidsremmende maatregelen resulteren in snelheidsreducties die beperkt zijn tot de directe omgeving van de maatregel heeft enkele implicaties op het wegontwerp. Op een macro niveau wordt er geadviseerd om steeds de ruimere context (zoals het nagaan of een weg eerder een verkeersfunctie dan wel een verblijfsfunctie heeft) in acht te nemen en om een goede selectie te maken van de potentieel gevaarlijke transities en discontinuïteiten om een overmatig gebruik van snelheidsremmende maatregelen te vermijden. Op meso niveau moet er nagegaan worden of implementatie van een combinatie van verschillende snelheidsremmende maatregelen over een langer traject het snelheidsreducerende effect van een voorgaande maatregel kan verlengen. Zo kan er nagegaan worden of de combinatie van een poortconstructie met een DIP de effectiviteit van het gehele snelheidsremmende maatregelenpakket kan verbeteren. Verder is de visuele link tussen een snelheidsremmende maatregel en de potentieel gevaarlijke situatie of locatie belangrijk om een gevoel van geloofwaardig snelheidsmanagement op te wekken en compenserend gedrag te voorkomen (vb. direct versnellen na een snelheidsremmende maatregel). Op micro niveau wordt er geadviseerd om het concept van vergevingsgezinde wegen (*forgiving roads*) toe te passen zodat de consequenties van een fout geminimaliseerd worden. Volgens de literatuur zijn obstakelvrije zones en botsvriendelijke obstakelbeschermers belangrijke ontwerpvoorbeelden.

Verder wordt de **toepassing van rijsimulatoronderzoek voor geometrisch wegontwerp** bediscussieerd. Ondanks dat rijsimulatoronderzoek wordt beschouwd als een geschikte onderzoekstool in ergonomisch wegontwerp moeten er enkele kanttekeningen geplaats worden bij deze aanpak. Daarnaast wordt de rol van rijsimulatoronderzoek beschreven binnen een globaal evaluatieproces dat kan gebruikt worden om de potentiële veiligheidseffecten van geometrisch wegontwerp proactief te onderzoeken.

Ten slotte worden enkele **ideeën voor toekomstig onderzoek** besproken. Het zou interessant zijn om, naast de verschillende onderzochte snelheidsremmende maatregelen, ook onderzoek te doen naar andere ontwerpconfiguraties. Daarnaast zou toekomstig onderzoek zich kunnen focussen op het bepalen van de optimale locatie van de snelheidsremmende maatregel ten opzichte van de transitie of de discontinuïteit (vb. wat is de optimale afstand tussen de TRS en de bocht), de optimale afstand tussen de markeringen van de TRS en het HP of de invloed van complementaire snelheidsremmende maatregelen in een doortocht of een bocht. Verder worden enkele suggesties gedaan om een systematische aanpak te verbeteren om de resultaten van lokaal en internationaal onderzoek op te nemen in ontwerphandboeken en –handleidingen.

Chapter 1

INTRODUCTION

1.1 ABOUT THIS DOCTORAL THESIS

Road safety is worldwide a serious problem which leads to high physical, psychological, material and economic costs (paragraph 1.2). The pro-active character of the **Safe System Approach** (paragraph 1.3), in which the human error proneness and vulnerability is recognized and accepted, provides a good starting-point to achieve the joint target to drastically reduce road fatalities and accidents (OECD & International Transport Forum, 2008; Chen & Meuleners, 2011; Larsson, Dekker, & Tingvall, 2010). The road safety measures in the context of the Safe System Approach take humans' limitations with respect to information processing capabilities and human's body tolerance into account. The, so called, ergonomic or human-centered road design incorporates human factors during the whole design process of the road and the road environment in order to avoid road accidents and minimize the accident severity (Campbell, Richard, & Graham, 2008; Keith et al., 2005; Weller, Schlag, Gatti, Jorna, & van de Leur, 2006).

A predictable and recognizable road environment can support a safe road transport system by means of the road layout which evokes driving behavior which is in line with the preferred behavior and reduces human errors (paragraph 1.4). This encourages the desired behavior in a given environment, and makes it easier for road users to predict the behavior of other road users and of the road course, thereby supporting road safety (Aarts & Davidse, 2006). On the contrary, unsafe situations are likely to occur if the perceived message conveyed by an environment does not match with the behavioral expectations of road users (Weller, Schlag, Friedel, & Rammin, 2008).

Lately, markers have been implemented in the context of the Dutch Sustainable Safety approach to support recognition of road segments and make roads self-explaining. Several studies indicate the importance of recognizable transitions (i.e., between two road categories) and discontinuities (i.e., major change in road design within the same road category) as an adaptation of the driver's expectation is required at these locations resulting in a behavioral adaptation. Nevertheless, research and design standards are rather scarce in this domain. Typically, transitions and discontinuities go together with an important change in speed management and/or level and focus of attention in order to maintain safe driving behavior. Based on the literature (e.g. Brouwer, Aarts, & Louwerse, 2008; CROW, 1997; in Wegman & Aarts, 2006; Koornstra, Mathijssen, Mulder, Roszbash, & Wegman, 1992; in Aarts, Davidse, Louwerse, Mesken, & Brouwer, 2005; Theeuwes & Godthelp, 1995), it can be concluded that additional insight in the design and influence of transitions and discontinuities are required.

This thesis focusses specifically on **traffic calming measures** (TCM) located nearby **rural-to-urban transitions** and **tangent-to-curve discontinuities** (paragraph 1.5). Both locations were selected based on their increased accident risk which is related to the transition from a rural to an urban area or with the passing of a curve. Both mental underload and an excessive and/or inadequate driving speed can cause unsafe situations. Five driving simulator studies were performed in order to investigate the potential of various TCMs. Gate constructions and several messages for digital information displays located nearby rural-to-urban transitions were investigated (Chapter 3). In addition, two pavement markings (transversal rumble strips (TRS) and herringbone pattern (HP)) were implemented nearby the tangent-to-curve discontinuity (Chapter 4). All these TCMs were investigated in cross-sectional driving simulator experiments where we were interested in the behavioral adaptions in distance (along the road) and whether we can make a distinction between the different TCM. For the gate constructions and the TRS two longitudinal driving simulator experiments were performed in order to examine the influence on driving behavior of repeated exposure. The medium-fidelity driving simulator of the Transportation Research Institute – Hasselt University was used in all experiments (Chapter 2).

1.2 ROAD SAFETY PROBLEM

Since a couple of decades, road safety is a topic that is correctly receiving a lot of attention. Road crashes and casualties lead to high physical, psychological, material and economic costs. Worldwide, about 1,25 million people die in traffic on a yearly basis and 3% of the gross domestic product (GDP) is lost to road fatalities and injuries (World Health Organization, 2015). In the European Union (28 countries), almost 25.700 people were killed in 2014 and more than 200.000 got seriously injured (European Commission, 2015) accounting for a 2% loss in GDP (Directorate-General for Mobility and Transport, 2013). Belgium and Flanders have only moderate results with respectively 724 and 384 fatalities in 2013. In addition, more than 2.900 people got seriously injured in Flanders (Carpentier, Schoeters, Nuyttens, Declercq, & Hermans, 2014). Compared with other European countries, Belgium (64 fatalities per million inhabitants) ends up in the lower middle of the list of 28 countries between Hungary and the Czech Republic whereas the Netherlands, Sweden and United Kingdom form the leading group in the field of road safety (with 26 to 29 fatalities per million inhabitants) (European Commission - Mobility and Transport DG, 2015). Figure 1 shows an overview of the mortality (fatalities per million inhabitants) in the European Union, Belgium and the three Belgian Regions for the period 1991-2014.

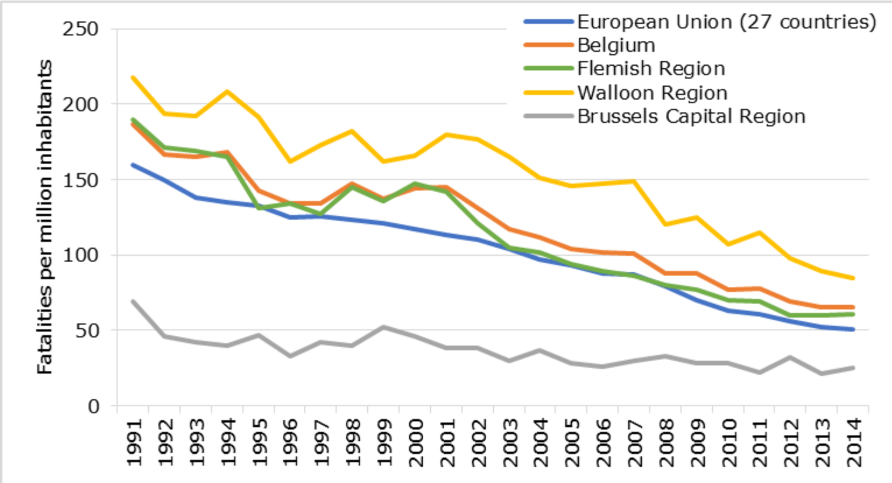


Figure 1 Evolution of the mortality (fatalities per million inhabitants) in the European Union, Belgium and the three Belgian Regions (1991-2014) (Federal Government Statistics Belgium, 2015)

The European Commission proposed to half the number of fatalities in the European Union by 2020 compared to 2010 (European Commission, 2010). The target of Flanders is even more ambitious with maximum 200 fatalities in 2020 (Vlaanderen in Actie, 2010) and 133 by 2030 (Vlaamse Overheid - Departement Mobiliteit en Openbare Werken, 2013). In order to achieve these targets, additional efforts are needed.

As mentioned in the Flemish Road Safety Plan (2008), the Safe System Approach from the Netherlands (Sustainable Safety) and Sweden (Vision Zero) can be a good starting-point for these additional efforts. As traffic accidents can rarely be attributed to one causal factor, both visions are based on an integrated system of traffic components (i.e. environment, vehicle and road users) wherein the road user is the yardstick of the whole system (CROW, 2008; Swedish Road Administration, 2009). Several studies (Rumar, 1985; in Shinar, 2007, p. 705; Treat et al., 1977; in Weller et al., 2006, p. 9) established that the road user had a causative influence in more than 90% of all road accidents. In addition, about one-third of all accidents can be related to the road environment (see Figure 2).

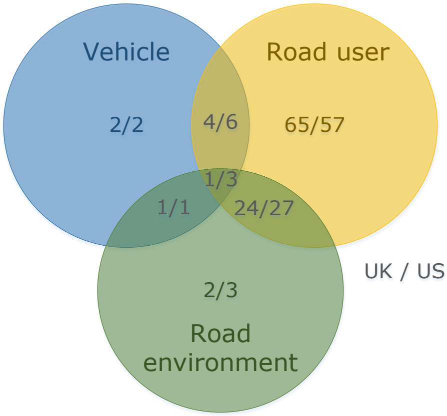


Figure 2 A comparison of the accident causative factors in United Kingdom and United States (based on Rumar, 1985; in Shinar, 2007, p. 705)

Although the road and the road environment play a causative role in only one third of all accidents, infrastructural interventions are an important policy measure. Besides the fact that a safe road environment can prevent accidents with an infrastructural causative nature, a human-centered road design can positively influence the driver's behavior to avoid accidents and a forgiving road environment can reduce the accident severity. Besides road safety, the Flemish government can influence the accessibility of facilities, the accessibility of all citizens to the transport system, a better traffic livability and a reduction in harm for nature and environment, in order to realize a sustainable road transport system (Vlaamse Overheid - Departement Mobiliteit en Openbare Werken, 2008). Another advantage of infrastructural measures is their long term lasting effect of a single intervention compared to educational or enforcement measures where continuous effort is required (SWOV, 2013).

1.3 Safe System Approach

During the past decades, several road safety policies evolved from a more traditional road safety approach, in which a re-active approach characterized the road safety policies and the individual road user was considered to be responsible for crashes and injuries, to a Safe System Approach. The basic idea of the Safe System Approach is to go beyond the traditional 'business as usual' road safety interventions, where diminishing cost-effectiveness of these traditional measures is established, and evolve to a pro-active road safety policy. This pro-active approach places the limitations of the road user at the center of attention. These limitations are related to human error on the one hand which can be linked to the limited cognitive characteristics of a human being (see paragraph 1.3.1), and to the limited human body's tolerance to physical forces on the other hand (see paragraph 1.3.2). As a result, the starting-point of the Safe System Approach is the recognition and acceptance of this human error proneness and vulnerability. Both the World Health Organisation (World Health Organization, n.d.) and the Organisation of Economic Cooperation and Development (OECD & International Transport Forum, 2008) recommend that all countries, irrespective of their road safety level, apply the Safe System Approach.

Human behavior, such as driving, is prone to unintended errors and is therefore an important contributing factor to road accidents (see Figure 2). Even if people are motivated to behave safely, latent errors – in combination with dangerous actions – may result in an accident. The so called Swiss Cheese Model (see Figure 3) illustrates how a specific chain of latent errors or conditions (e.g. inadequate design, training or procedures, failures in maintenance) and dangerous actions, passing all barriers without resistance, may result in an accident. These barriers should be designed to prevent accidents and refer for instance to engineering safety features, active and passive safety systems, training, rules and regulations (Salmon, Cornelissen, & Trotter, 2012; Theeuwes, van der Horst, & Kuiken, 2012).

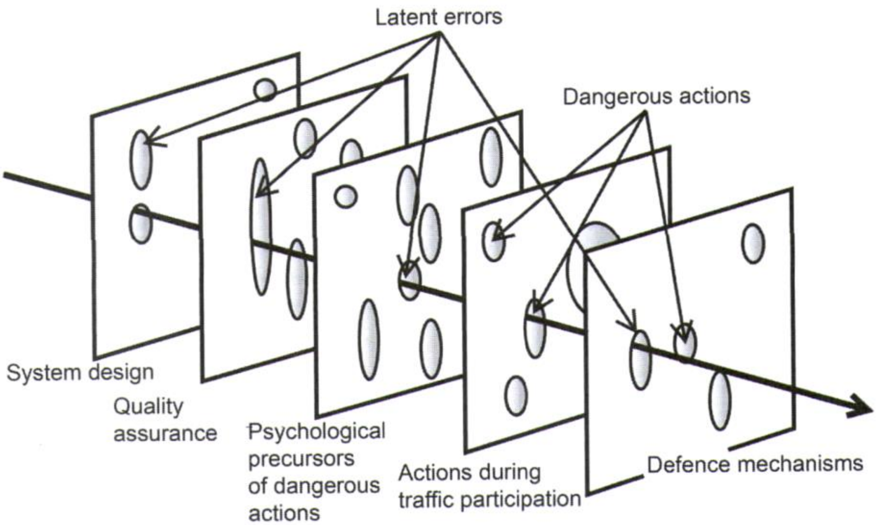


Figure 3 Swiss Cheese Model (Reason, 1990; in Theeuwes et al., 2012, p. 28)

In order to improve road safety, a human-centered design, in which human's limited capabilities and vulnerability are taken in account, is required to minimize the occurrence of human errors. As this thesis focusses on road design, concepts like 'safety by design' or 'prevention through design' aspire an efficient reduction of the accident risk because they work in a pro-active manner and intervene in the first layers of the Swiss Cheese Model to prevent accidents while a forgivingness road environment minimize the accident severity at the end of the Swiss Cheese Model. This, so called, ergonomic or human-centered road design takes this Swiss Cheese Model into account and incorporates human factors during the whole design process of the road and the road environment in order to avoid road accidents and minimize their severity (Campbell et al., 2008; Keith et al., 2005; Weller et al., 2006). In conclusion, an important focus of the Safe System Approach is a human-centered road design, incorporating human factors during the whole design process of the road and the road environment in order to avoid road accidents and minimize the accident severity.

Furthermore, the Safe System Approach creates a 'stronger safety culture' by incorporating a higher level of vision including more individual and societal commitment to road safety throughout the whole transport system (OECD & International Transport Forum, 2008). The organization of the Safe System Approach postulates a 'shared responsibility' with respect to road safety among the different actors of the road transport system (e.g. road users, policy makers, engineers, planners etc.) in order to achieve the joint target of drastically reducing road fatalities and accidents (OECD & International Transport Forum, 2008; Chen & Meuleners, 2011) (see paragraph 1.3.3). Each layer in the Swiss Cheese Model can be linked to one or more actors of the road transport system and represent their responsibility to prevent accidents and minimize accident severity. This is in line with the research of Ottino (2003, p. 293; in Salmon, McClure, & Stanton, 2012) stating: "*Complex systems cannot be understood by studying parts in isolation. The very essence of the system lies in the interaction between parts and the overall behaviour that emerges from the interactions. The system must be analysed as a whole*".

Starting from this Safe System Approach, the following paragraphs elaborate on the human factors which are at the center of attention in a human-centered road design. A behavioral model is first described in order to understand the most important capabilities and limitations of human information processing while driving (paragraph 1.3.1). Furthermore, the human body's vulnerability is elaborated in paragraph 1.3.2. Although it is not the focus of this thesis, the 'shared responsibility' concept among all actors of the road transport system is shortly introduced in paragraph 1.3.3. Finally, some applications of the Safe System Approach in national road safety strategies are discussed in paragraph 1.3.4.

1.3.1 Human capacities and limitations

Human errors during driving are an important causal factor for road safety (see Figure 2) and are the result of a series of internal behavioral processes in the road user. These internal behavioral systems are described by a variety of traffic psychologists. Based on a literature review of the behavioral models of Wickens (1992), Shinar (1978) and Endsley (1995) (in Shinar, 2007) an integrated behavioral model for information processing is composed (see Figure 4).

As this thesis focusses on the impact of traffic calming measures on driving behavior and will not examine the internal human processing mechanism, this model is not empirically tested. However, the basic comprehension of the behavioral model is an added value in order to understand the driver's internal processes while driving through the conditions tested in this thesis.

A. Stimuli and limited capabilities

During a trip the driver is exposed to a series of stimuli which are or are not related to the driving task. Stimuli detection during the driving task is mainly visual (90%) whereas other senses are involved for a smaller part (10%) (Babbitt, Ghali, Kline, & Brown, 1990; Bartmann, Spijkers, & Hess, 1991; in Charlton & O'Brien, 2002). Vibrations due to imperfection in the road surface or pavement markings (such as transversal rumble strips) or centrifugal forces in curves are some road infrastructure related examples which produce non-visual stimuli.

Information processing is characterized by the human's limited capacity. Task demands during the driving task are determined by at least two factors: speed and complexity of the driving task. Firstly, a higher speed is related to an increased amount of stimuli the driver is exposed to in a given time interval. Secondly, the more complex the road, the larger the information stream between two points on that road. A complex road environment demands more information processing capacity in comparison with a simple road environment (Shinar, 2007). The limited information processing capacity forces drivers to filter relevant information from the huge information stream and makes the system efficient (Leclercq & Zimmermann, 2002). The capacity is among others dependent on the level of attention and the short-term memory (STM) and long- term memory (LTM).

B. Four components of information processing

The limited capacity requires the road user to filter the stream of stimuli and to process the information before executing some responses.

Perception

The infinite information stream (shown by ⬭△■ in Figure 4) is scanned by the senses of the road user and relevant and salient features are extracted whereas part of the information is not further processed (Wickens, 1992; in Shinar, 2007). When the driver detects the stimuli, he tries to find a logical pattern by using his STM and LTM (e.g. schemata). The speed of this recognition is determined by the amount and completeness of the schemata which in turn depend on the experience of the driver.

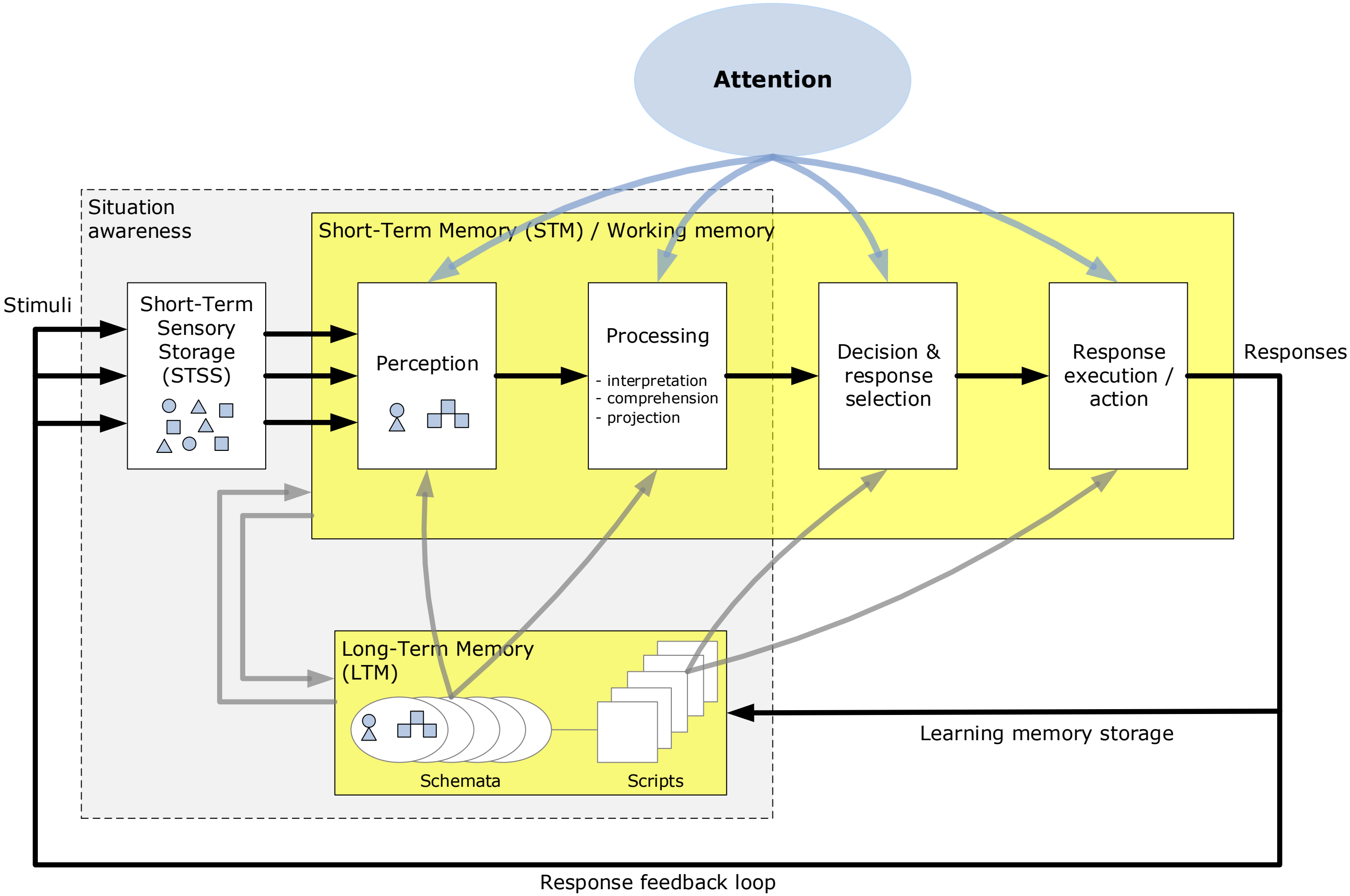


Figure 4 Behavioral model for information processing (adapted from Wickens (1992), Shinar (1978) and Endsley (1995) (in Shinar, 2007))

Processing

The processing of the perceived stimuli consists of three consecutive steps: interpretation, comprehension and projection. The schemata in the LTM play a crucial role because they contain the frames with the interpretation and meaning of the perceived patterns of the stimuli. The more extensive and complete the schemata are, the easier and more correct the interpretation and comprehension of the stimuli is. The last step of the processing component is the projection of the information in time and space (Ma & Kaber, 2005). On the basis of the perceived information stream the driver tries to make a prediction of the road, the environment and other road users in time and space. To prevent an accident the driver has to predict what the traffic situation will be like in a few seconds. On the basis of this prediction the driver will take a decision on an action in the next step.

Decision and response selection

During the decision process the driver is led on the one hand by the perceived information and on the other hand by his motives and unconscious processes (Ajzen & Fishbein, 2005; De Pelsmacker & Janssens, 2007; Fishbein et al., 2001; Thaler & Sunstein, 2008). The driver's decision is based on the processed information and is derived from the scripts in the LTM. The decision making process is more difficult in complex situations and for inexperienced drivers. The strong relationships between the huge amount of schemata and scripts of an experienced driver lead to quasi automatic decisions. The appropriateness of a decision depends largely on the attention level. When a driver pays insufficient attention to the driving task, the perception and processing of the incoming stimuli are diminished which results in less processed information to base decisions on and increases the chance of wrong decisions.

Response execution or action

The script which is activated in the previous step is executed in this last step of the information processing process. The correctness and speed of the action depend on the experience and fitness of the driver, the applied attention level, the road environment and the location of the different control elements on the dashboard in the vehicle.

C. Responses and feedback loop

The resulting responses of the information processing contain all possible actions which a driver executes during his driving task. The actions result in a change of the lateral and longitudinal position of the vehicle and influence the 'status' of the vehicle (for example turning left at an intersection, passing a curve at a lower speed). As a result, the stimuli to which the driver is exposed will also change. Due to the response feedback loop the driver can perceive the changes. Information processing is thus a continuous process to react properly to the changes. According to Kadar and Shaw (2000), drivers can predict a future course of action and (i.e., feedforward processing) thereby anticipate to corrective actions (i.e., feedback processing).

D. Attention

Due to the limited information processing capacity of humans, the driver is forced to pay attention to the information stream and filter out only the relevant stimuli. The efficiency of this behavior is thus determined by the capacity of the attention system (Leclercq & Zimmermann, 2002). Klauer, Dingus, Neale, Sudweeks and Ramsey (2006; in Shinar, 2007) define attention as a source of psychic energy which people spend on each task at any time.

Due to the limited capacity, distributing attention is more difficult than focusing attention. Research (Hendrickx, Fell, & Freedman, 2001; Sabey & Staughton, 1975; in Shinar, 2007) shows that these limitations of attention are one of the most important causes of accidents.

E. Relationship between human factors and road safety - Fuller's task-capability interface model

According to Fuller (2005), drivers seek for task difficulty homeostasis. In Fuller's model, drivers compare their driver capability with the task demands. The driver capability is mainly determined by the driver's characteristics such as information processing speed and capacity, driver experience and motivation. On the other hand, environmental factors (e.g., horizontal and vertical road design, visibility, road signs, etc.), vehicle's trajectory, the driving speed and other road users determine the task demand. In case the demands exceed the capability a loss of control can lead to a collision or a lucky escape. The level of capability that is allocated in this situation is lower than the task demand that is needed for safe driving behavior which – depending on the forgivingness of the road and compensation of other road users – may or may not lead to an accident (Leclercq & Zimmermann, 2002; Shinar, 2007). When the demanded attention level is exceeded, the driver has the opportunity to slow down or to stop completely so that the incoming amount of information strongly decreases and the spare attention is allocated to the driving task.

The task difficulty thus varies not only as a function of changing road demands, but also as a function of fluctuating capabilities allocated to the driving task. The driver can vary his driving capability, within the boundaries of the total limited capacity, by paying less or more attention to his non-driving tasks or to parts of the driving task. The driver can choose to change his speed so that the amount of incoming stimuli in a certain time period decreases or increases. A speed reduction will result in less prominent fluctuations of the (environmental) task demands such that the driver has more time to adapt his behavior (driver capability) to the changing circumstances. When driving at a high speed on the other hand, the peak in the attention demand is much larger which results in little time to respond to the changing environmental demands. Moreover the driver covers more distance during that time such that a more complex (critical) situation is more likely. If the driver does not reduce his speed in complex situations, demanded attention increases and more attention is thus required to cope with the huge fluctuations (Godley, 1999). The environmental demands are thus proportional to the speed and the complexity of the environment.

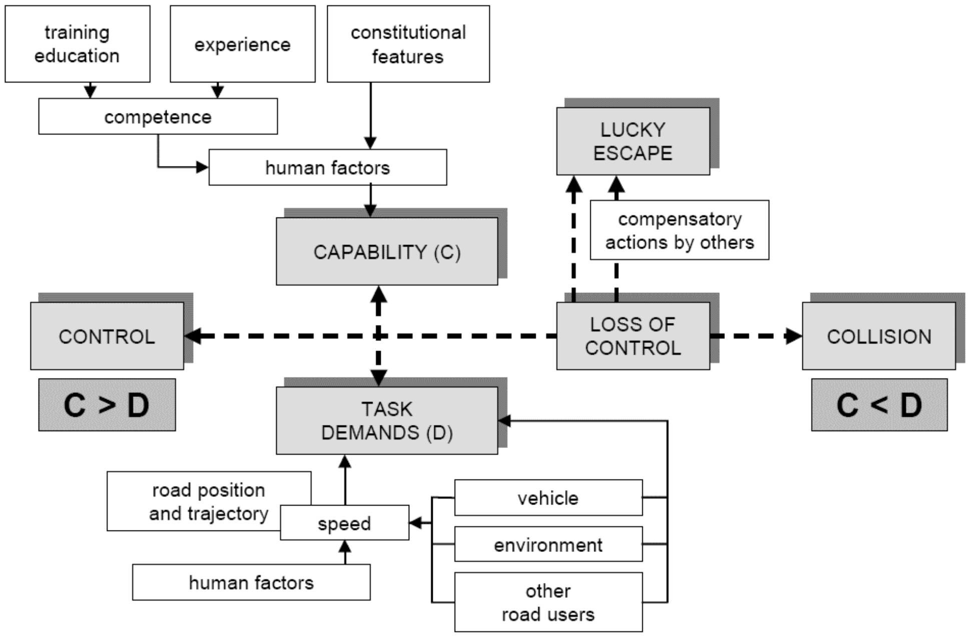


Figure 5 Fuller's task-capacity interface model (Fuller, 2005; in Weller et al., 2006)

F. Expectation and readability

According to the model of Blumenthal it is important that drivers set their attention for the driving task at a correct level so that their capability to perform the driving task does not exceeds the environmental demands. The resulting driving performance is, according to the Yerkes-Dodson law (Fuller, 2005; Van Knippenberg, Rothengatter, & Michon, 1989; Weller et al., 2006), dependent on the arousal or workload level at that moment and the difficulty of the task. Both very low and very high workload levels lead to lower performance levels. The performance is thus best at medium workload levels. This optimum level shifts to the right for easy tasks and to the left for complex tasks.

The driver himself can vary his workload level by changing the speed. This is according to Fuller (2005) also the primary solution but it can provoke speeding. On the other hand, a creation of rhythm in the road environment – by for example a sequence of trees, curves, striking buildings or changing distances between buildings – also increases the workload level. A monotonous road, such as a highway or an open rural road, is the extreme counterpart of a rhythmic road and stimulates highway hypnosis in which a driver ends up at a very low arousal level or even falls asleep (Cerezuela, Tejero, Chóliz, Chisvert, & Monteagudo, 2004; Thiffault & Bergeron, 2003).

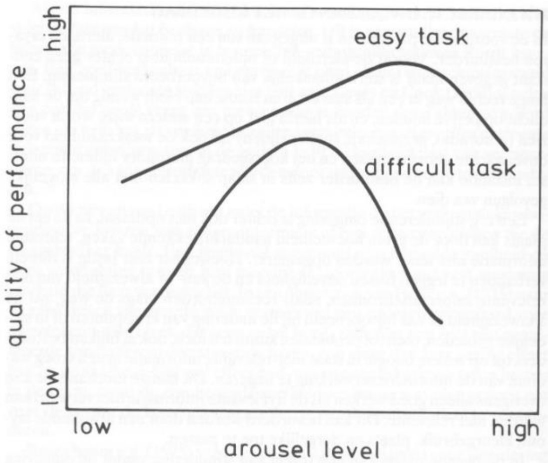


Figure 6 Yerkes-Dodson law (Van Knippenberg et al., 1989)

A determinant for the allocated attention level is the expectations on behalf of the driver about the approaching road environment. A driver will increase his level of attention for the driving task or reduce his speed when he is expecting a complex traffic situation (Cnossen, Meijman, & Rothengatter, 2004). In the case of a monotonous road, the low workload level for the driving task will be compensated by an increase of the speed or by allocating more attention to non-driving tasks to achieve the optimal arousal level (Shinar, 2007).

Road designers try to find a balance via the concept of predictability and readability which means that a road user should know which behavior is expected from him. A driver should thus estimate the environmental demands well. The schemata and schemes in the LTM are an important tool to do this and a predictable and recognizable road environment can support the driver in safe driving (see paragraph 1.4.1).

G. Speed behavior

Based on the model of the internal behavior system described in this thesis (see Figure 4), we can conclude that the driving speed plays an important role in road safety. More specifically, the size of the information stream – in terms of stimuli – is approximately directly proportional to the speed and the complexity of the environment. High driving speed in a complex road environment requires more attentional resources from the driver in order to perceive and process the relevant information and make the right decisions to execute. Due to the limited information processing capabilities of a human being, the driver might fail to anticipate on time to the changing road situation or lose control over the vehicle.

Perception of speed

The driver's actual speed choice is the result of the external stimuli and internal factors processed by the internal behavioral system. Both internal factors (such as age, sex, risk acceptance, habits, motives and attitudes) and external factors (such as road environment, vehicle characteristics, speed signs, weather conditions and elements which divert the driver's attention away from the driving task) influence these internal systems (Campbell et al., 2012; De Pelsmacker & Janssens, 2007; Elliot et al., 2003; European Commission, 1999; SWOV, 2012a; World Health Organization, 2004). Because it is difficult to change the driver's habits, motives and attitudes via infrastructural measures and traffic calming measures, which is the focus of this thesis, these internal factors are not further discussed. Nevertheless, information processing by the driver – in which the attention level plays a central role – in relation to the perception of speed is discussed.

The driver's visual perception of the road environment is the most important cue for speed estimation and driving in general. The literature shows that approximately 90% of the required information for driving comes from the visual environment. The auditory, haptic and proprioceptive senses account for only 10% of the input (e.g. Hartman, 1970; Hills, 1980; Lay, 1986; in Godley, 1999; Ogden, 1996). For example, drivers tend to underestimate their driving speed with diminished hearing (e.g. Denton, 1966, 1976; Evans, 1970; in Godley, 1999) or vibration cues (Thomas J. Triggs & Berenyi, 1982).

Each time a driver consults a speedometer, the actual speed can be compared with the perceived and required speed. Research of among others Triggs (1986), Evans (1970), Milosevic and Milic (1990) and Recarte and Nunes (1996) (in Evans, 2004; and Godley, 1999) shows that – despite the repetitive practice of consulting a speedometer during driving – drivers are not that good in judging the actual driving speed. According to Shinar (1978; in Godley, 1999) speed is observed by the perception of the optical flow from the visual environment. This optical flow originates at the focus of expansion, a fixed point at the horizon, and expands outwards in the visual field of the driver. Figure 7 shows the optical flow.

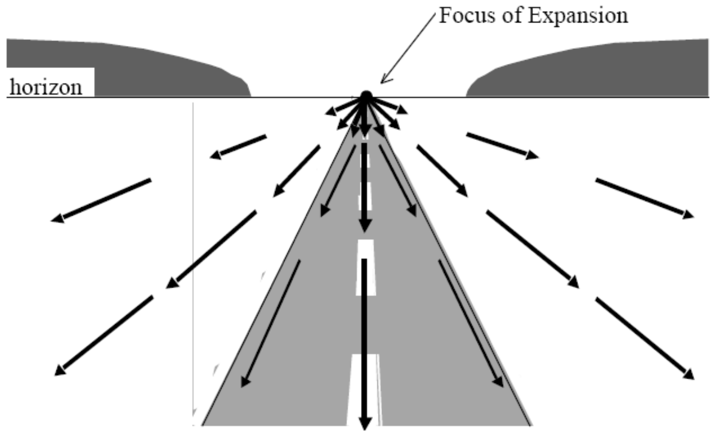


Figure 7 Motion perspective of elements in a visual field when moving forward on a straight road (Gibson, 1950; in Godley, 1999)

The arrows represent the direction of the flow whereas the relative velocity of the elements in the visual field is shown by the length of the arrows. In 1965 Gordon (1965) defined the motion paradox: if looking straight ahead when moving, the velocities of the elements are inversely proportional to the distance from the observer. It is thus the peripheral visual field which forms the main cue for visual speed perception. This finding is confirmed by Salvatore (1967, 1968; in Godley, 1999) who found that speed estimations from peripheral vision are higher and more accurate than they are through foveal vision. This can be explained by the differences in the range of change of the visual angle – defined as the angular velocity – to elements in the driver's visual field. The central vision records smaller angular velocities than the peripheral vision with the largest angular velocities in the most extreme regions of the peripheral vision (Godley, 1999). Furthermore, peripheral vision is more sensitive for motion detection that focal vision (Salvatore, 1967, 1968; Shinar, 1978; in Godley, 1999). This explains the fact that driver's speed is higher in an wide perspective in comparison to a narrow perspective.

Besides the fact that drivers generally underestimate their speed and that peripheral vision is the main visual cue for speed, the visual field shrinks and gets deeper with increasing speed (Bartmann et al., 1991; in Charlton & O'Brien, 2002). This results in less peripheral information about the vehicle's movement which might lead to a speed overproduction (Denton, 1969; Recarte & Nunes, 1996; Tada, Kitamura, & Hatayama, 1969; in Godley, 1999). Finally, it is important to mention that speed perception is also influenced by tactile (vibrations) and auditory (engine and rolling noise) stimuli (Campbell et al., 2012).

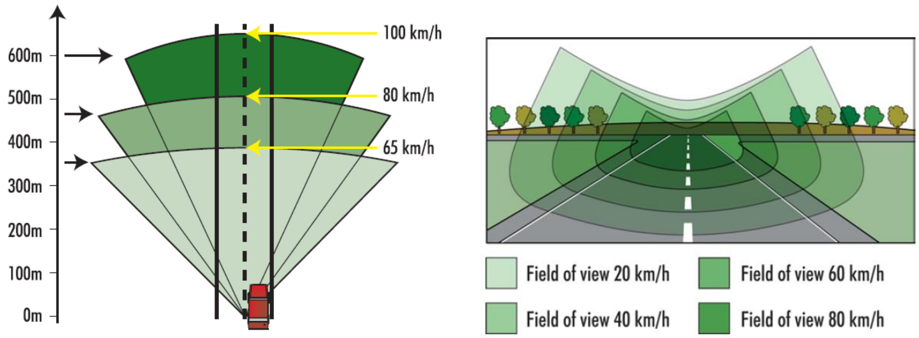


Figure 8 Narrower and deeper visual field with increasing speeds (PIARC, 2003, p. 432)

Furthermore, motion at a constant (high) velocity over a prolonged time might result in speed adaptation. Drivers perceive their speed to be slower than usual (Denton, 1976; in Godley, 1999; Evans, 1970; Recarte & Nunes, 1996; Snider, 1967; in Charlton & O'Brien, 2002) and this effect is more pronounced after rapid deceleration because of the visual motion after-effect (VMAE) (Denton, 1976; Schmidt & Tiffin, 1969; in Godley, 1999). The results of Denton's study also suggest that this underestimation will increase as the exposure to a constant speed lasts longer.

The larger speed underestimations due to speed adaption can have important negative consequences for road safety. This is especially the case at the end of long constant velocity roads, such as at motorway exit ramps, at the entrance of a built-up area after driving on an open rural road at a constant speed or at a curve preceded by a long tangent (i.e., straight road section (PIARC, 2003)). Speed underestimation is an important contributor to excessive speed which is in turn a major contributing factor to road accidents (Godley, 1999). This brings us to the next paragraph in which the relationship between driving speed and accident risk is elaborated.

Driving speed and accident risk

Two pillars form the basis of the relationship between speed and road safety, i.e., accident risk and injury severity (European Commission, 1999; Shinar, 2007; SWOV, 2009). According to the National Highway Traffic Safety Administration (1997) speed is an important contributory factor in 30% of all fatal accidents. Firstly, the risk of an accident increases as the speed increases. This is the result of a longer braking distance and a shorter time to process and react to the fast information stream from the environment. As illustrated in Figure 9, longer reaction and braking distances result in higher accident risk for a pedestrian running into the road at 13 meters in front of a vehicle (World Health Organization, 2008). Furthermore, vehicle stability and vehicle control reduce at higher speeds and contribute to higher accident risks (PIARC, 2003).

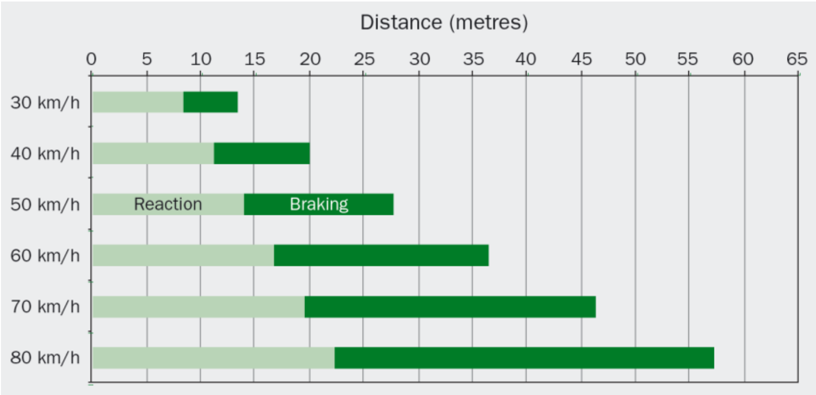


Figure 9 Illustration of the stopping distance for an emergency brake (World Health Organization, 2008, p. 7)

Moreover, several studies established that crash rates increase more rapidly when driving speed increases and vice versa (Gargoum & El-Basyouny, 2016; Safetynet, 2009b; SWOV, 2012a; World Health Organization, 2008). Nilsson (1982; in Safetynet, 2009b; & SWOV, 2012a) developed – based on the basic kinetic laws – a power model for injury accidents showing the effect on crash risk as a result of an increase or decrease in average driving speed on a road segment.

$$Accidents\ after = Accidents\ before \cdot \left(\frac{Speed\ after}{Speed\ before}\right)^2$$

Several researchers re-analyzed the basic power formula of Nilsson and concluded that "*the effect of a given relative change in speed (e.g. -10%) depends on the initial level of speed*" (R. Elvik, 2009, p. ii). More in detail, changes in relatively low speeds (below 60 kph) tend to have lower impact on the accident risk compared to changes in relatively high speeds (above 60 kph) As a result, Elvik (2009) revised the exponent of Nilsson's model and made a distinction between rural roads or freeways on the one hand and urban or residential roads on the other hand, showing lower values for the exponent for the latter road types.

In addition, the accident risk is higher in more complex road environments with intersections and a mix of other road users compared to low complexity road types such as a motorway (M. Taylor, Baruya, & Kennedy, 2002; M. C. Taylor, Lynam, & Baruya, 2000; in Safetynet, 2009b). Furthermore, the variation of speed on a road segment also has an important influence on the accident risk. On the one hand larger speed differences across the different road users results in less predictable driving behavior and more overtaking behavior, resulting in higher accidents risks. On the other hand, drivers that divert more from the average speed are more often involved in accidents (Aarts & van Schagen, 2006; Kloeden, McLean, & Glonek, 2002; Kloeden, McLean, Moore, & Ponte, 1997; Kloeden, Ponte, & McLean, 2001).

Finally, the severity of an accident increases exponentially as the speed increases which results from the huge impact forces. This relationship is further elaborated in paragraph 1.3.2.

1.3.2 Physical vulnerability of road users

The limited human body's tolerance to physical forces is, besides the limited information processing capabilities (see paragraph 1.3.1), an important fundament of the Safe System Approach.

Figure 10 shows that as the speed increases the accident severity increases exponentially due to the huge impact forces. In addition to the relative speed difference, the difference in mass between road users plays also an important role. In general, the kinetic energy absorption is inversely proportional to the mass of the road user. Although vehicles are equipped with a variety of passive safety measures (such as seatbelts, airbags and crush areas), which have to protect occupants and other road users for severe injuries, the collision speed remains an important factor in the severity outcome of an accident.

Following the basic power formula of Nilsson (see paragraph 1.1.1 0), comparable formulas were developed in order to estimate the effect on the number of victims and their severity as a function of the relative change in driving speed. The form of the basic power formula remains the same, however the exponent will change based on the accident severity and the road type (R. Elvik, 2009).

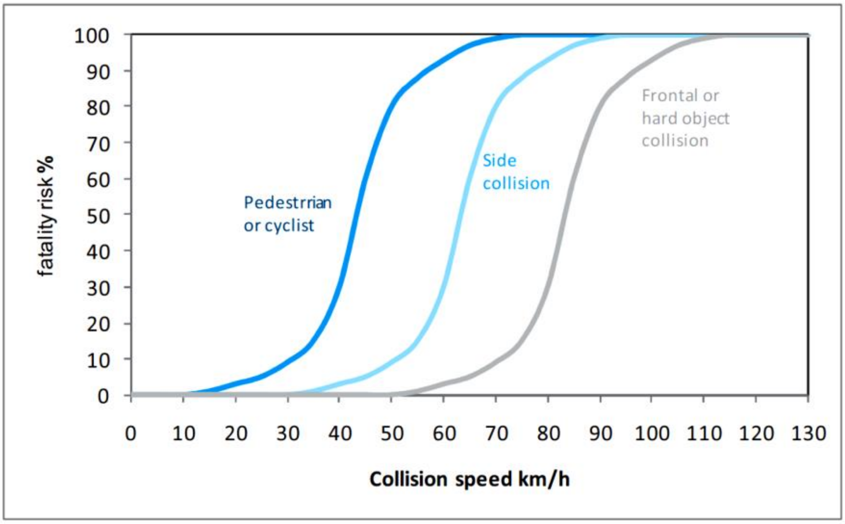


Figure 10 Fatality risk for three major crash types at different impact speeds (Wramborg, 2005; in OECD & International Transport Forum, 2008, p. 112)

In conclusion, excessive (i.e., above the posted speed limit) and inappropriate speed (i.e., too fast for the given road conditions) is a very important road safety issue. Studies investigating the causative factor in accidents estimated that in about one-third of all fatal accidents speeding was involved (Safetynet, 2009b; SWOV, 2012a; World Health Organization, 2008).

1.3.3 'Shared responsibility' among the different actors of the road transport system

The Safe System Approach creates a 'stronger safety culture' by incorporating a higher level of vision including more individual and societal commitment to road safety throughout the whole transport system (OECD & International Transport Forum, 2008). The organization of the Safe System Approach postulates a 'shared responsibility' with respect to road safety among the different actors of the road transport system (e.g. road users, policy makers, engineers, planners etc.) in order to achieve the joint target of drastically reducing road fatalities and accidents (OECD & International Transport Forum, 2008; Chen & Meuleners, 2011) (see paragraph 1.3.3). Each layer in the Swiss Cheese Model can be linked to one or more actors of the road transport system and represent their responsibility to prevent accidents and minimize accident severity. Both road users and those who plan, design, operate and maintain all parts of the system should work together and share the responsibility to achieve an inherently safe road transport system for all road users. This is in contrast with the traditional road safety policies, where individual road users were often blamed for the cause and the severity of an accident (Larsson et al., 2010).

An inherently safe road system is, as described by the Swiss Cheese Model (see Figure 3), the result of the presence of optimally designed layers where latent errors or dangerous actions are stopped and accidents are avoided. These layers can be represented by the different actors in the road transport system. As a result, the Safe System Approach assigns not only an important role to the individual road users and to the road and vehicle designers in order to minimize the accident risk and severity, but also other parties like policy makers, government agencies, police, transport companies, education, user groups and lobbyists and other actors have to share this responsibility.

Although this 'shared responsibility' is considered as an important organizational aspect, the literature about the practical elaboration in specific, operational measures or strategies is rather limited discussed in this thesis because it was not the focus of this thesis. Nevertheless, the following key concepts are summarized from national road safety strategies:

- Swedish Vision Zero: "*Everyone shares responsibility for making traffic safer: politicians, planners, road maintenance organizations, municipalities, transport service providers, vehicle manufactures, and road users*" (Hughes, Anund, & Falkmer, 2015, p. 273)

- Australian's National Road Safety Strategy (2011-2020): "*Shared responsibility and corporate responsibility. Responsibility for road safety is shared by all*" (Hughes et al., 2015, p. 273)
- Wegman, Aarts and Bax (2008) acknowledge that the first decennia of the Dutch Sustainable Safety programme put a lot of effort on knowledge sharing and dissemination. However, they recommend for the Advancing Sustainable Safety programme to spend even more effort on knowledge and knowledge-management. In addition, two visions on the public administration implementation of Sustainable Safety are discussed and are summarized in Table 1. According to the authors, the network approach in a multi-stakeholder setting will be the most likely because of the current decentralization trend in the Netherlands.

Table 1 Two visions on the implementation of Sustainable Safety (Wegman et al., 2008, p. 340)

Implementation as rational programming	**Implementation as coordination process in a multi-stakeholder setting**
Sustainable safety is an effective concept that has to be implemented as completely and uniformly as possible	Sustainable safety is not static. It is about realizing uniformity and an adequate adaptation in dialogue with executive organizations
Central control is the best guarantee for a complete and uniform implementation	Central control leads to adaptation problems and alienates potential partners, whereas central government failed as an ally in the past
Area-oriented policy and faceted policy are detrimental to uniform and complete implementation	Area-oriented policy and faceted policy offer opportunities for adaptation of sustainable safety at decentralized level and proactive involvement of related policy areas
Success is the extent to which the realized measures comply with the ideal of sustainable safety	Success is comprised of road safety benefits relative to existing situations
Research institutes contribute to the content of sustainable safety based on their scientific knowledge	Knowledge about sustainable safety facilitates regional and local authorities and other actors in the preparation of measures with road safety impacts

1.3.4 Application of the Safe System Approach in national road safety policies

During the past decades, several road safety policies evolved from a more traditional road safety approach to a Safe System Approach. Besides the implementation of the Australian's Safe System Framework (e.g. OECD & International Transport Forum, 2008; Regional Integrated Transport Strategy Implementation Advisory Group (RITS IAG), n.d.), Vision Zero in Sweden and Sustainable Safety from the Netherlands are the most well-known and elaborated examples of the Safe System Approach. Although it is not the intention of this thesis to describe these programmes in detail, a short overview of these three programmes is presented below. In addition, the Belgian and Flemish road safety policy is examined in the framework of the Safe System Approach.

A. Australia – National Road Safety Strategy

The Australian Transport Council defined two National Road Safety Strategies within the holistic view of the Safe System Approach, one for the period 2001-2010 and a more recent for the period 2011-2020. The key cornerstones of this last strategy are the realization of safe roads, safe speeds, safe vehicles and safe people in order to minimize accident risks. Therefore the following guiding principles are defined (Hughes et al., 2015; RoadWise, 2015):

- *"The limits of human performance: we all make mistakes and we all need to acknowledge the limits of our capabilities.*
- *The physical limits of human tolerance to violent forces: we are physically vulnerable when involved in a traffic crash.*
- *Shared responsibility: this means all of us take an individual and shared role in road safety.*
- *A forgiving road system: so that when crashes do happen, deaths can be avoided and injuries minimized."*

B. Sweden – Vision Zero

Sweden adopted the Vision Zero approach since 1997 and states that "*the long-term goal for Swedish road safety policy is that nobody should be killed or seriously injured in the transport system*" (Rosencrantz, Edvardsson, & Hansson, 2007, p. 559). The basic assumption of Vision Zero is that road users will make errors and, in order to anticipate to these errors, considers roadway and vehicles designers together with the road user responsible for this (Fahlquist, 2006; Keith et al., 2005; OECD & International Transport Forum, 2008; Swedish Road Administration, 2009). This responsibility is defined as follows (Johansson, 2009, p. 827):

- "*The designers of the system are always ultimately responsible for the design, operations and use of the road transport system and are thereby responsible for the level of safety within the entire system.*
- *Road users are responsible for following the rules for using the road transport system set by the system designers.*
- *If road users fail to obey these rules due to a lack of knowledge, acceptance or ability, or if injuries do occur, the system designers are required to take the necessary further steps to counteract people being killed and seriously injured.*"

Furthermore, the Swedish Transport Administration (n.d.) published in 2008 the report "The management of traffic safety work by objectives. Cooperation between players focusing on new milestones in 2020". This means that a number of Safety Performance Indicators are used to follow up targets and annual result conferences are used to evaluate the fulfilment of these targets with respect to the road safety trends (Swedish Transport Administration, 2014; Aarts, Bax, & Dijkstra, 2014). Three fundamental points were proposed to manage traffic safety by objectives: *"Cooperation when milestones are developed, action-related milestones and annual result conferences in which traffic safety and goal fulfilment are evaluated"*.

The kinematic energy in crashes is managed by means of the integration of traffic elements and the separation of road users. The following eight road design principles were defined (Johansson, 2009, p. 829):

1. *"Vulnerable road users should not be exposed to motorized vehicles at speeds exceeding 30 kph.*
2. *If 1. cannot be satisfied then separate or reduce the vehicle speed to 30 kph.*
3. *Car occupants should not be exposed to other motorized vehicles at speeds exceeding 50 kph in 90° crossings.*
4. *If 3. cannot be satisfied then separate, or reduce the angle, or reduce the speed to 50 kph.*
5. *Car occupants should not be exposed to oncoming traffic (other vehicles of approximately same weight) at speeds exceeding 70 kph or 50 kph if oncoming vehicles are of considerably different weight.*
6. *If 5. cannot be satisfied then separate, homogenize weights or reduce speeds to 70 (50) kph.*
7. *Car occupants should not be exposed to the road side at speeds exceeding 70 kph, or 50 kph if the road side contains trees or other narrow objects.*
8. *If 7. cannot be satisfied separate or reduce speed to 70 (50) kph."*

The adoption of the Vision Zero approach by the Swedish parliament is recognized as an example of a radical innovative road safety policy (e.g. Belin, Tillgren, & Vedung, 2012). However, some authors formulated some criticism with respect to the elimination of fatal accidents. For example, Elvik (1999; 2003) advises to prioritize investments in measures with the highest marginal rate of life-saving instead of absolutely prioritizing on road safety. Ekelund (1999; in Rosencrantz et al., 2007) on the other hand states that each individual should be free to take the risk he prefers. As a result, the author argues that there should be no goal for road safety. Finally, Lind and Schmidt (1999; in Rosencrantz et al., 2007) state that the goal of Vision Zero is not always taken serious and not considered as a real goal.

Notwithstanding these critical reflections, the Swedish Transport Administration showed that in 2013 the reductions in fatally and seriously injured road users were in line with the required trend to the 2020 intermediate targets (Swedish Transport Administration, 2014).

C. The Netherlands – Sustainable Safety

The Netherlands was also a pioneer in the Safe System Approach. Their Sustainable System originates in the idea that traffic is inherently unsafe. The general objective of Sustainable Safety is defined as "*prevent road crashes from happening, and, where this is not feasible, to reduce the incidence of (serious) injuries whenever possible*" (Wegman et al., 2008, p. 330). The user-centered approach forms the starting-point for all measures which are linked to the integrated '3 E approach' in which policies are developed related to Education, Enforcement and Engineering.

In 1997 the Sustainable Safety Start-up Programme was launched. At that time the first three Sustainable Safety principles were defined. In 2006, with the advent of the updated version entitled Advancing Sustainable Safety, two principles were added, resulting in five Sustainable Safety principles which are summarized in Table 2 (Wegman et al., 2008; Weijermars & Wegman, 2011).

Table 2 The five Sustainable Safety principles (Wegman et al., 2008, p. 330)

Sustainable Safety principle	**Description**
Functionality of roads	Mono-functionality of roads as flow roads, distributor roads or access roads, in a hierarchically structured road network
Homogeneity of masses and/or speed and direction	Equity in speed, direction, and masses at medium and high speeds
Forgivingness of the environment and of road users	Injury limitation trough a forgiving road environment and anticipation of road users
Predictability of road course and road user behavior by a recognizable road design	Road environment and road user behavior that support road user expectations through consistency and continuity in road design
State awareness by the road user	Ability to assess one's task capability to handle the driving task

The operationalization of these Sustainable Safety principles within the context of infrastructural road design is the development of the categorization of roads. This is further elaborated in paragraph 1.4.

Although it is difficult to estimate precisely the road safety improvements which are specifically generated by the implementation of Sustainable Safety, the following effects were reported:

- 6% reduction of all fatalities and serious injuries in the period 1997-2002 due to the complete package of infrastructural Sustainable Safety measures (Wegman et al., 2008).
- In comparison to a scenario in which crash and fatality rates and policy remained the same, 30% reduction of fatalities in 2007 due to the introduction of all measures which are based on the Sustainable Safety vision (Weijermars & Schagen, 2009).

- Forecasting models, taking different mobility scenarios and new policy measures into account, predicted that, if additional measures are taken, the policy target of 500 fatalities in 2020 is feasible (Wesemann, Norden, & Stipdonk, 2010).

D. The Belgian and Flemish road safety policy

Belgium and Flanders did not develop their own strategy with respect to the Safe System Approach. However, the Flemish Road Safety Plan (Vlaamse Overheid - Departement Mobiliteit en Openbare Werken, 2008) refers to Vision Zero and Sustainable Safety as international standards with respect to road safety and expresses its intention to integrate these strategies in the Flemish road safety policy. In addition, the Flemish Spatial Plan (Ministerie van de Vlaamse Gemeenschap, 2004; Vlaamse Overheid, 2011) and the Mobility Plan Flanders (Ministerie van de Vlaamse Gemeenschap, 2001) describe the application and implementation of the concept of road categorization which is recognized as an important practical operationalization of the Sustainable Safety principles. Recently, the new Mobility Plan Flanders (Vlaamse Overheid - Departement Mobiliteit en Openbare Werken, 2013) adopted the vision and principles of Sustainable Safety. Finally, in 2014 the Flemish Government published a manual for forgiving roads, which is an operationalization of the forgivingness principle of Sustainable Safety (Vlaamse Overheid, 2014).

1.4 ROAD CATEGORIZATION AND SELF-EXPLAINING ROADS

In order to improve road safety, a human-centered road design in which human's limited capabilities are taken in account is required to minimize the occurrence and severity of human errors. The Dutch Sustainable Safety facilitates this vision by defining five guiding principles (see Table 2).

The operationalization of the Sustainable Safety principles within the context of infrastructural road design is the development and implementation of a categorization of the road network. CROW (CROW, 2012, p. 11) defined road categorization as: *"[…] the draw up of a vision on a safe road network with a for the road user recognizable design– by means of mutual harmonization of the traffic and environmental influences – where persons and goods can travel smooth, safe and efficient, taking the livability into account*".

As this thesis focusses on transitions and discontinuities in road categorization, the approach to set up the categorization of the road network will not be elaborated. Matena et al. (2006) provide an overview of road categorization practices in Europe. In addition, more information can be found in the CROW publication "*Basic characteristics for road design*" (CROW, 2012). Notwithstanding, the basic principles of road categorization with respect to road design are described firstly whereas in the second part transitions and discontinuities in road categorization are elaborated.

1.4.1 Road categorization principles

The main principle of road categorization originates in the **functionality** of roads. The Dutch and Flemish government both agreed upon three main road functions: through roads, distributor roads and access roads (Ministerie van de Vlaamse Gemeenschap, 2004; SWOV, 2010). The traffic function, in terms of high speeds and high traffic flows for through traffic, characterizes the through roads. On the contrary, access roads provide access to destinations. The residential function, where different road users mix at low speeds, prevails. Finally, distributor roads connect both rather contrary road functions with each other. At the road segments the traffic function is most important, whereas intersections make the exchange between different roads possible. An overview of European road categorization practices shows that the road function and its hierarchy in the network are the main determinants in the categorization system (Weller & Dietze, 2010). However, the design of the road environment and operating characteristics (e.g., posted speed limit and traffic flow) are also important determinants to categorize the road network (Koszotolanyi-Ivan, Koren, & Borsos, 2016).

A second important issue regarding the design principles of a road category is the human's physical vulnerability which forms the basis for the **homogeneity** principle. Traffic that differs in speed, mass and/or direction should be separated and if this is not possible, speeds should be reduced. This will result in a smoother traffic flow and lower speeds at intersection. In case two road users collide, the kinetic forces are limited and the chance for sustaining serious injury is minimized (SWOV, 2010). The same idea forms the starting-point for the **forgiving** principle where the road environment ensures that the consequences of an error are reduced to a minimum. Obstacle-free zones and collision-friendly obstacle protections are important design examples (La Torre, 2012; Nitsche, Saleh, & Helfert, 2010; SWOV, 2010; Vlaamse Overheid, 2014).

In order to achieve a safe road environment, human's limited capabilities should also be taken into account. A **predictable and recognizable** road categorization can support this by means of the road layout which evokes driving behavior which is in line with the preferred behavior and reduces human errors. A consistent road design and continuous road course are important aspects of a predictable layout. The idea of credible speed limits is also closely related to this predictability principle. Van Schagen, Wegman and Roszbach (2004) define a credible speed limit as "*a speed limit that matches the image that is evoked by the road and the traffic situation*". A logical and credible outlook of the road and its environment is important for drivers to match their expectations with the posted speed limit. The photo survey of Goldenbeld and colleagues (2007; 2006) established that the credibility of speed limits is influenced by a variety characteristics of the road environment, e.g. the road width, presence or absence of a curve, view ahead and to the right, situation complexity and presence or absence of buildings or trees on the right side of the road.

Theeuwes and Godthelp were the founders of the Self-Explaining Road (SER) concept and described it as "*Traffic systems having self-explaining properties are designed in such a way that they are in line with the expectations of the road user. The so-called 'Self-Explaining Road' is a traffic environment which elicits safe behavior simply by its design*" (Theeuwes & Godthelp, 1995, p. 217). A standardized road category should therefore look different among the other categories in order to be distinguished. On the other hand they should emit uniformity within the same category in order to be recognizable. Finally, the specific road characteristics of a particular road category should induce the desired behavior and therefore be easily interpreted (Theeuwes et al., 2012). In conclusion, it takes the limited human processing capabilities into account.

The schemata in the long term memory of the driver (see Figure 4) contain internal mental structures and rules that represent similar events and situations. By ordering and structuring situations into a limited number of categories, people try to order their world. This mechanism is essential in order to filter the enormous (mainly visual) information stream. Based on repeated exposure to a particular object, internal representations of the characteristics associated with a category are formed. In addition, the behavior associated with these characteristics is stored in the schemata and expectations are recalled with respect to the own behavior and that from other road users (Aarts, Davidse, & Christoph, 2006; Matena et al., 2008; Theeuwes et al., 2012). Once a specific road category is recognized, the driver will behave in a more homogenous and predictable way resulting in more routine behavior, fewer errors and a reduction in crash probability (Aarts et al., 2006; SWOV, 2012b). This process is visualized in Figure 11.

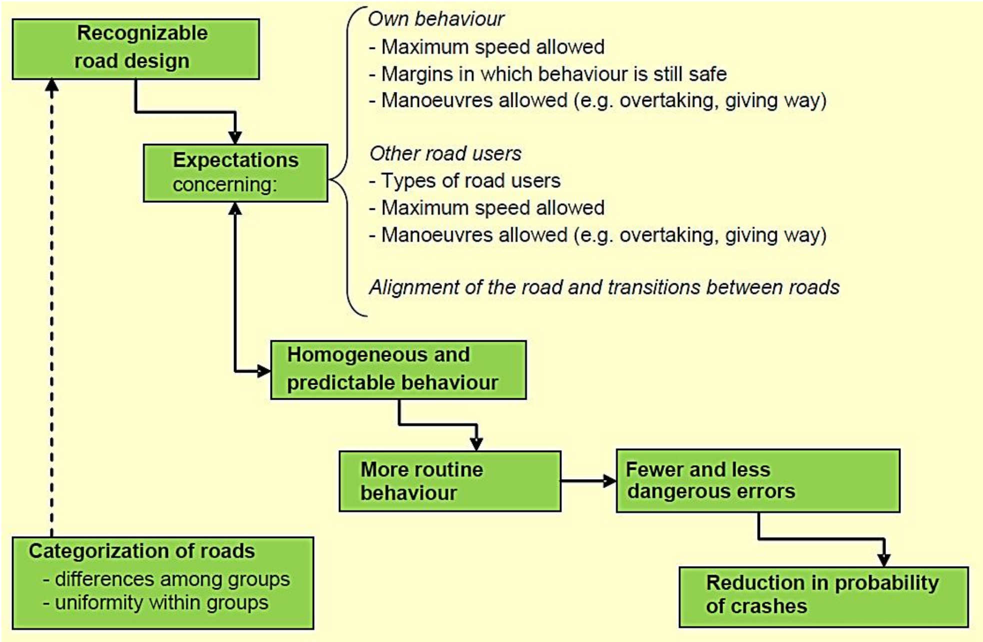


Figure 11 Chain of recognizable road layout and predictable behavior as suggested in Sustainable Safety (SWOV, 2012b, p. 2)

Furthermore, it is important to note that the subjective road categorization, defined as the experienced road categorization and the associated behavioral expectations, is an important predictor for actual driving behavior (Theeuwes et al., 2012). Weller and colleagues (2008) developed a 'driver and driving behavior model for rural roads' (see Figure 12) to describe the processes behind the subjective and behaviorally relevant road categorization.

Research with respect to this mental categorization showed that drivers can distinguish four (Matena et al., 2008) to five or six (Koszotolanyi-Ivan et al., 2016) different road categories. However, an overview of national road categorization approaches in Europe shows that countries identify 4 (Norway and Germany) to 15 (Hungary) different road categories on their road network. However, 8 to 10 different road categories are more typical (Koszotolanyi-Ivan et al., 2016; Weller & Dietze, 2010). Notwithstanding the initial intention to minimize the number of road categories to three functions, the current Flemish road categorization system defines nine different road categories with their own design principles (Ministerie van de Vlaamse Gemeenschap, 2004).

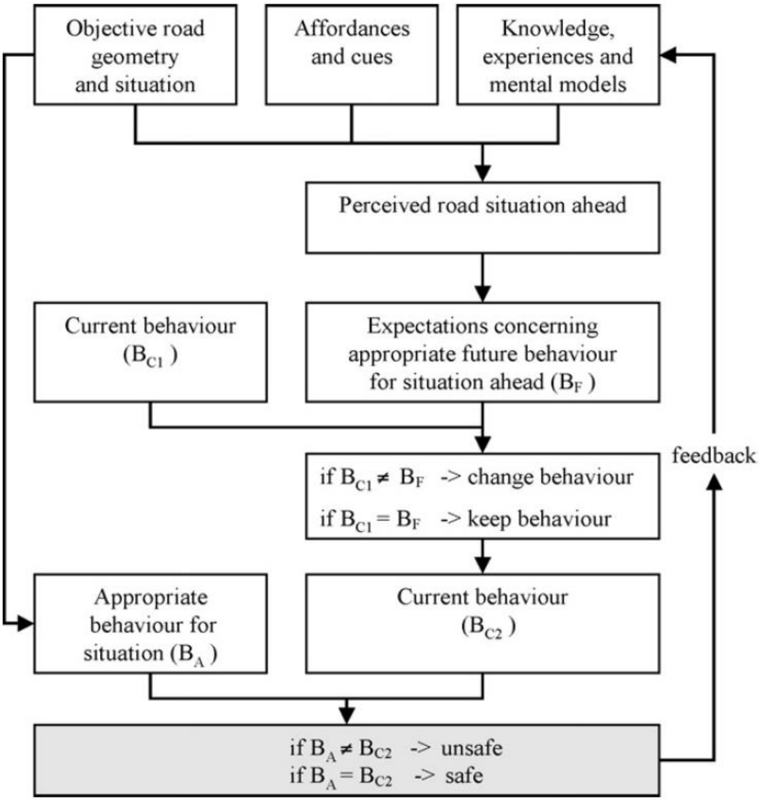


Figure 12 Driver and behavior model for rural roads (Weller et al., 2008, p. 1583)

Besides the number of different road categories in the network, the number of road design characteristics should also be limited. In addition, these design characteristics should be continuously perceivable, be practically implementable and not have a negative effect on road safety (van Schagen, Dijkstra, Claessens, & Janssen, 1999). Based on literature review, Aarts, Davidse and Christophe (2006) defined eight road characteristics which can contribute to a recognizable road environment. However, in order to be practically implementable on a shorter term the Dutch National Mobility Council officially acknowledged in 2003 only driving direction separation, edge markings and a zone sign as three 'Essential Recognizable Characteristics' (ERC) of sustainable safe roads (see Figure 13).

Essential Recognition Characteris-tics	Flow-road		Distributor road	Access road
Speed limit	**120 km/h**	**100 km/h**	**80 km/h**	**60 km/h**
Road sign	 (ASW, G01)	 (AW, G03)	no	 (A01(60) / E10)
Road side/edge marking	unbroken	unbroken	broken	broken or none
Separation of driving direc-tions	wide median or barrier	double axis mark-ing with 'green' filling, or median	double axis marking (without filling), or median	no
				

Figure 13 Essential Recognizable Characteristics according to the Sustainable Safe Principle (Matena et al., 2006, p. 104)

The implementation of these ERCs is a first step towards a sustainable road network. Other markers that should support the recognition of a road environment, such as forgiving road elements, (red) cycle lanes, a good horizontal alignment and different intersection types per road category, are an important next step towards sustainable safer roads. Other countries follow a comparable approach as the Netherlands. For example, Matena and colleagues (2006) made an overview and compared the road categorization design principles of Germany, Denmark and the Netherlands. In order to limit the variation on design variants and combine the ERC with other road safety characteristics, the CROW manual "*Basic characteristics for road design*" (CROW, 2012) defines which characteristics and minimum road design variants are essential for a sustainable safe design.

Although a variety of research is executed in order to investigate the relationship between a number of road design characteristics and the related expectations and executed behavior, not all choices in the CROW guideline document are evidence-based. Picture sorting tasks (e.g. Koszotolanyi-Ivan et al., 2016; Martens, Kaptein, Claessens, & van Hattum, 1998; Weller et al., 2008), driving simulator research (e.g., Aarts et al., 2006; Daniels, Vanrie, Dreesen, & Brijs, 2010; Kaptein, Janssen, & Claessens, 2002), surveys (e.g., Goldenbeld & van Schagen, 2007) and observational studies (e.g., Charlton et al., 2010; Goldenbeld & van Schagen, 2007; Herrstedt, 2006; Mackie, Charlton, Baas, & Villasenor, 2013) were executed in order to get insight in expectations (related to the presence and behavior of other road users) and driving speeds with respect to specific road design characteristics. Important to note, most of these experiments were related to design characteristics of road segments. As the focus of this thesis is related to transitions and discontinuities in road categorization we will not further elaborate on the results of these experiments. For an overview of the research related to self-explaining design characteristics for road segments we would like to refer to Charman et al. (2010), Charlton et al. (2010) and Theeuwes, van der Horst and Kuiken (2012, pp. 18–22).

1.4.2 Transitions and discontinuities in road categorization

In the previous section, the basic principles for road categorization are explained and the main focus relates to road segments. However, it is also important to take transitions into account. This was already recognized by Theeuwes and Godthelp (1995, p. 224) who stated that self-explaining roads should fulfill (among others) the following tentative criteria:

- *"The layout of crossings, road sections and curves should be linked uniquely with the particular road category*
- *The same category should connect a section which psychologically is interpreted as a single unit*
- *There should be no fast transitions going from one road category to the next*
- *When there is a transition in road category, the change should be marked clearly"*

Although it is clearly recognized in several documents in the nineteens (e.g. CROW, 1997; in Wegman & Aarts, 2006; Koornstra et al., 1992; in Aarts et al., 2005; Theeuwes & Godthelp, 1995) that recognizable transitions between different road categories or between a rural and urban area is essential in order to evoke the right expectations in the driver, it took until 2008 when a first literature review about recognizable category transitions in road design was published (Brouwer et al., 2008). This literature review described four transition types:

- Transition between road categories which, according to the literature, go together with an intersection
- Transition between road functionalities: transition between traffic and access functions by means of an intersection with a distributor road
- Transition between speed regimes within the same road category (example: transition on a through road where the speed limit of 100 kph changes to 120 kph)

- Transition in the road environment with or without a required adaptation of the drivers' behavior (i.e., speed management and attention level).

In this thesis a **transition** is defined as the short road segment where a change in road category or road functionality takes place and where an adaptation of the behavior of the driver is required through a set of correct expectations on how one has to behave in order to be driving safely. More specifically, the transition should result in an important change in speed management and/or the level as well as the focus of attention of the driver. Some examples are the transition from a rural through road to an urban access road (Figure 14) or the transition from a motorway (i.e., through road) to a distributor road by means of a variety of motorway exit design principles or intersection types (Figure 15).

Figure 14 Rural to urban transition

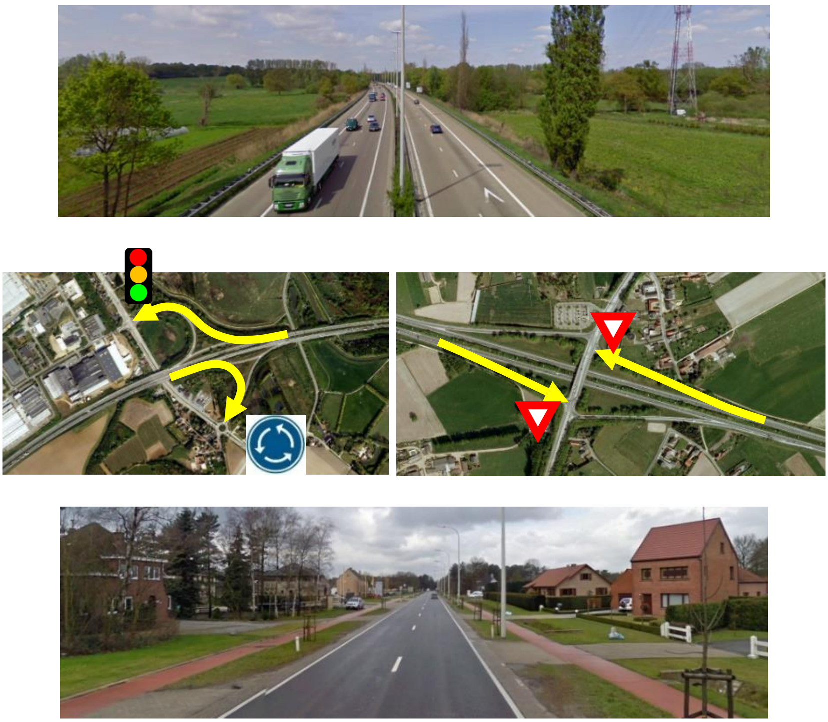


Figure 15 Transition from motorway to distributor road

As intersections play also an important role in transitions, Mesken and colleagues (2010) and Stelling-Konczak et al. (2011) performed experiments in which the predictability and recognizability of several road layouts and intersection types at transitions between road categories were investigated. Based on five consecutive photographs (two photos of a first road, one photo from an intersection and two photos from a second road) and animated movies participants had to indicate their expectations with respect to the speed limit and the presence of other road users. The results showed that unique intersection types (priority intersections instead of roundabouts), physical separation between driving directions and green center markings (but only with additional information) increase the recognizability of the transition between two different road categories.

Although it is recognized that the design of transitions is important regarding a Sustainable Safe road design, standardized guidelines or research with respect to the recognizability of transitions is rather scarce. The CROW manual "*Basic characteristics for road design*" (CROW, 2012) defines some characteristics for transitions and preferred design variants for intersections between road categories. Unfortunately, this manual does not further elaborate on specific design standards. However, design characteristics for a recognizable transition are even more important when the distinction in design of road segments of two different road categories is absent (Aarts & Davidse, 2006). Although on the longer term it is expected that in the Netherlands all road segments are designed according to the ERC, it is still uncertain that road users will recognize the transitions. Therefore, further research with respect to the recognizability of transitions and the accompanied changes in speed management and attention level is required. The objective of this thesis is to examine the potential of various design concepts of rural-to-urban transitions. More information about the specific aim and research questions is described in paragraph 1.5.

Besides transitions, we focus also on **discontinuities** where an adaptation of the driving behavior is required due to a major change in road design within the same road category or road functionality and the resulting set of correct expectation on how one has to behave in order to be driving safely. Although the road category or functionality does not change, drivers have to adapt their speed and/or level and focus of attention to the changing road design. This change in road design is often the result of an inadequate design of a longer road segment where a specific part of the road stretch has deviating design characteristics compared to the preceding road environment. Some examples are the discontinuity between a tangent and a curve, see Figure 16) or a sudden interruption of a road segment (e.g., while passing a rail level crossing). In an optimally designed road environment, discontinuities should be minimized by means of an adequate road design of the whole road segment serving the Sustainable Safe design principles. However, in expectation of the redesign of these discontinuities, (low-cost) measurements can be implemented in order to improve the safety near these discontinuities. In this thesis we investigate the potential of various pavement markings nearby tangent-to-curve discontinuities. Paragraph 1.5 gives more information about the specific aim and research questions.

Figure 16 Discontinuity from tangent to curve (star indicates point of curvature)

'Change blindness' is an important phenomenon which is applicable to both transitions and discontinuities. Galpin, Underwood and Crundall (2009, p. 180) define 'change blindness' by "*an inability to notice a change in two pictures presented alternately providing they are separated by a brief flicker, eye blinks, mudsplashes, or saccades, or if one is simply attending to something else (inattention blindness)*". Change blindness is inextricably bound up with attentional processes in the visual information processing by the road user. Therefore, the transition or discontinuity should attract the attention of the road user in order to be detected by the road user. The phenomenon of 'looked but failed to see' is present when a driver looks at something but does not pay attention to it and therefore does not see it. This phenomenon plays a role in approximately 10% of the road accidents (CROW, 2008; Shinar, 2007). The 'looked but failed to see' error can be attributed to the expectations of the driver: drivers pay no (or less) attention to objects they do not expect in a certain situation (Brouwer et al., 2008). Therefore, the Sustainable Safety principle intends to fit the road design and environment with the expectation of the road user.

The distribution of fixations and saccades depends on the visual search pattern of the driver. In the case of an internally driven search or 'search conspicuity' the driver himself is looking for information (Martens, 2000). Expectations about the place where information can be found are very important and are supported by the LTM. The danger that only the objects are seen which are expected is real. When striking or unexpected elements attract the driver's attention, this is referred to as externally driven search or 'object conspicuity' (Martens, 2000). Several driving simulator studies (Shinar, Mcdowell, & Rockwell, 1977; in Shinar, 2007) show that drivers fix their eyes on the focus of expansion on the horizon (Figure 7) and on the right hand side of the road because road signs are placed there. They explored that drivers follow a back-and-forth pattern with their eyes when driving on a curved road.

Once the transition or discontinuity is detected by the road user, he should change his expectations and behavior in the preferred way. As excessive and/or inadequate speeds and attention levels are a major contributing factor in accident risk and severity (see paragraph 1.3.1 0 and 1.3.2), traffic calming measures near/at transitions or discontinuities can be implemented in order to induce a more correct and safer speeding behavior. Furthermore, the implementation of credible speed limits can improve their speed choice (Goldenbeld & van Schagen, 2007). The concept of traffic calming measures in the context of self-explaining roads is described in paragraph 1.4.3.

1.4.3 Traffic calming measures in the context of self-explaining roads

Excessive and/or inadequate driving speeds are too often an important causative factor in accidents. A clear speed policy is therefore required. Wegman and Aarts (2008, p. 336) describe a phased plan to attain sustainable safe speeds:

- *"to identify criteria for safe and credible speed limits and minimum requirements for road user information*
- *to survey the road network in order to assess if the road environment and the existing speed limits are in conformity with each other, and to implement adaptations (to the road environment or the speed limit) where necessary*
- *to re-orientate regarding enforcement of speeds of intentional violators*
- *to prepare for and to introduce dynamic speed limits"*

This thesis focusses specifically at the speed adaptation to the road environment near transitions and discontinuities. More specifically we focus at traffic calming measures in the context of self-explaining roads. **Traffic calming measures** (TCM) are defined as "*the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behavior and improve conditions for non-motorized street users*" (ITE Institute of Transportation Engineers & FHWA Federal Highway Administration, 1999, p. 2). TCMs exist in a variety of shapes and dimensions with differentiations in both vertical (e.g., raised intersections and speed humps) and horizontal direction (e.g., chicanes). Some of the TCMs physically force drivers to adopt a certain driving speed, while other TCMs influence road users psychologically. The latest form of TCMs is often referred as 'perceptual countermeasures'. Fildes and Jarvis (1994, p. 1) describe this as follow: "*these treatments tend to be relatively low cost additions or modifications to the road or the immediate roadside setting that can lead to a change in the way the driving environment is perceived by drivers"*. The SPACE (Speed Adaptation Control by Self-Explaining Roads) project defined a clear link between the SER-concept on the one hand and TCMs on the other hand. They focus on TCMs that "*influence the sensory perception and cognition of road users*" (Charman et al., 2010, p. 19). Martens et al. (Martens et al., 1997, p. 30) expected that unintentional speeding behavior may disappear as drivers will adopt a driving speed which is in line with the expectations evoked by the road environment.

Several studies, such as Fildes and Jarvis (1994), Martens, Compte and Kaptein (1997), Elliot (2003) and Charman and colleagues (2010), describe an overview of the effects of a variety of TCMs. In general, the surrounding context and type of measure have a large influence on the established results (Dixon et al., 2008; Forbes, 2011; Hallmark et al., 2007).

In the context of rural to urban transitions, the County Surveyor's Society (1994) analyzed 24 village traffic calming schemes and obtained mean speed reductions between 2 kph and 16 kph. The Federal Highway Administration (2009b) reported speed reductions up to 24 kph in France, Denmark and the UK. However, speed reductions of 8-10 kph appear to be more typical (Department for Transport, 1993). Studies have found overall speed reductions of 2.3 kph up to 16.1 kph when a digital information display was installed (Bloch, 1998; Fontaine & Carlson, 2001; Mattox, Sarasua, Ogle, Eckenrode, & Dunning, 2007; Walter & Broughton, 2011). However, no lasting effect is observed once the digital information display is removed (Bloch, 1998; Walter & Broughton, 2011). Hallmark et al. (2007) examined seven low-cost TCMs in a before-after field experiment (data collection at 1-, 3-, 6-, 9- and 12-month intervals) and obtained changes in 85th percentile speed from -14 kph to +6 kph. However, a detailed look at the results showed that, while the speed reduction effect of some TCMs sustained over time or even increased, other speed reductions diminished under repeated exposure. This 'habituation' effect is also reported by Charlton and colleagues (2002). Driving simulator studies (Dixon et al., 2008; Federal Highway Administration, 2010; Galante et al., 2010) showed speed reductions from 6.4 to 17 kph for TCM in the transition zone. However, the results of Dixon et al. (2008) and Galante et al. (2010) indicate that these speed reductions do not consistently extend beyond the vicinity (300 to 400 m) of the TCM.

In order to induce appropriate speed and lateral control in tangent to curve discontinuities, several studies proposed a wide variety of pavement markings (i.e., directional arrows, centerline or shoulder rumble strips and (peripheral) transversal strips) and signs (i.e., (dynamic) warning signs, advisory speed signs and (chevron) alignment signs) (Charlton, 2004, 2007; Comte & Jamson, 2000; Federal Highway Administration, 2012; Hallmark, Smadi, & Hawkins, 2014; Katz, 2004; McGee & Hanscom, 2006). Elliot, McColl and Kennedy (2003; in Charlton & Baas, 2006) reported localized speed reductions between no effect up to 9,6 kph for transverse groupings of rumble strips. Godley (1999) established speed reductions between 8 and 11 kph near intersections and curves equipped with transverse lines. These results are in line with the speed reduction effects near intersections reported by Montella et al. (2011) (i.e., between 3 and 15 kph). Nevertheless, Rossi et al. (2013) found only moderate speed reductions for optical transversal speed bars near roundabouts (i.e., up to 2 kph). According to Elvik, Although these auspicious results, there is some doubt about the durability (both in time and distance) of the speed reduction effects (Comte & Jamson, 2000; Gates, Qin, & Noyce, 2008). The literature review of Martens et al. (1997) described that some experiments found that effects remained stable after a year (Zaidel, Hakkert, & Barkan, 1986), while others report that the effects lessen after some weeks or days (Maroney & Dewar, 1987).

As described above, the established effects of TCMs on speed change in distance (along the road) and in time (under repeated exposure). In the context of speed enforcement research, Hauer (1982) defined the terms 'distance halo effect' and 'time halo effects' (Hauer et al., 1982; in Vaa, 1997, p. 373):

- *"Distance halo effect is the number of kilometers from the enforcement site – be it downstream or upstream – in which the effect is maintained.*
- *Time halo effect is defined as the length of time during which the effect of enforcement is still present after police activity has been withdrawn."*

The definition of distance halo effect clearly applies to the context of TCMs and is examined in various field experiments and driving simulator experiments (e.g. Charlton, 2004; S. Jamson, Lai, & Jamson, 2010; Molino, Katz, & Hermosillo, 2010; Montella, Galante, Mauriello, & Pariota, 2015a; Santiago-Chaparro, Chitturi, Bill, & Noyce, 2012). However, as TCM are often fixed infrastructural measures which are installed for a longer time period (e.g. several years), the effects in time has to be considered as the result of a repeated exposure to the same TCM in time. In field experiments speed measures are collected before the implementation and several weeks and months after the implementation of the TCM (e.g. Hallmark et al., 2007, 2008; Ullman & Rose, 2005). Driving simulator research in this context is rather scarce. In the studies of Jamson and Lai (2011) and Rossi et al. (2013a, 2013b) subjects participated during one single simulator session during which each participants passed respectively four and ten times the same infrastructural measurements.

Paragraph elaborates more on the specific selection of TCM nearby rural-to-urban transitions and tangent-to-curve discontinuities and describes the specific aims and research questions of this thesis.

1.5 OVERVIEW OF AIMS AND STUDIES

The aim of this thesis is to provide more insight in the impact of different types of TCMs located nearby rural-to-urban transitions and tangent-to-curve discontinuities on driving behavior. More specifically, the **general objective** of this thesis is:

To examine the effects in distance (along the road) and time (under repeated exposure during 5 consecutive days) of traffic calming measures near road transitions and discontinuities.

In Chapter 3 we focus on the **transition between rural and urban areas**. From the perspective of road safety engineering, a speed reduction is often implemented within the transition zone to urban areas serving not only a residential function, but also a traffic function (i.e., allowing the traffic to drive through). But in many situations speed limits on rural roads are higher than in the urban area, and drivers have experienced a sustained period of driving at higher speed before accessing an urban area. This might have detrimental effects leading to reduced cognitive arousal and workload (i.e., *mental underload*), and the risk of underestimating the actual travel speed, (i.e., a phenomenon referred to as *speed adaptation*). As explained in paragraph 1.3.1, mental underload and speed adaptation can cause unsafe situations, mainly because of the inadequate way in which speed reduction is performed (Dewar & Olson, 2007; Galante et al., 2010; Hallmark et al., 2007; NRA National Roads Authority, 2005; Safetynet, 2009b). Furthermore, Wegman and Aarts (2006) indicate that – although the transition might be clear for the road designer – this is not always the case for the road user. They give the examples of "*a road in a rural area with an urban speed limit, or a road with many adjacent buildings, but with a rural speed limit*" (Wegman & Aarts, 2006, p. 81). Appropriately designed transition zones are therefore of crucial importance for road safety.

Forbes (2011) grouped the transition zone treatments into four categories: geometric design (e.g., chicanes or central islands), traffic control devices (e.g., variable message signs or speed cameras), surface treatments (e.g., speed humps or transverse rumble strips) and roadside features (e.g., as gateways or landscaping). Within this wide range of possible measures, in this thesis **gate constructions** were implemented at rural-urban transitions and **digital information displays** (DID) were installed near the transition. Three different digital messages were investigated:

- A social approval/disapproval logo: a DID with a laughing smiley when the driver's speed is below the speed limit; otherwise a sad smiley

- A social approval/disapproval text message: a DID with the text "You are speeding" when the driver is exceeding the speed limit; otherwise "Thank you"
- A deterrence message: a DID with a warning sign "Speed enforcement"

Chapter 4 focusses on the **discontinuity between long tangents and dangerous curves**. Curves typically are associated with an increased safety risk: accident rates are 1.5 to 4 times higher than in tangents (i.e., straight road sections) and 25 to 30% of all fatal accidents occur in curves. Single-vehicle run-off-road accidents represent approximately 60 to 70% of all fatal curve-related accidents, whereas head-on collisions occur in 11% of the fatal crashes (Safetynet, 2009a; Srinivasa et al., 2009). Charlton (2007) proposed three main causative factors for accidents in curves, i.e., inappropriate speed monitoring, failure to maintain proper lateral position, and the inability to meet increased attentional demands. Milleville-Pennel, Jean-Michel and Elise (2007, p. 721) describe that 72% of the accidents in curves have "*excessive speed and/or steering wheel errors*" as major contributing factors. Extensive experimental research on human factors and road design determined that these behavioral problems often relate to the geometric properties of curves (Brenac, 1996; R. Elvik, Hoye, Vaa, & Sorensen, 2009; Khan, Bill, Chitturi, & Noyce, 2013; Safetynet, 2009a). Unfortunately, these geometric design properties are hard to change on the short term with a limited budget.

In order to induce appropriate speed and lateral control in curves, a wide variety of additional infrastructural traffic control devices has been proposed such as signs (i.e., (dynamic) warning signs, advisory speed signs, (chevron) alignment signs and delineators) and pavement markings (i.e., directional arrows, centerline or shoulder rumble strips and (peripheral) transversal strips) (e.g. Charlton, 2004, 2007; Comte & Jamson, 2000; Federal Highway Administration, 2012; Hallmark, Hawkins, & Smadi, 2013; Katz, 2004; McGee & Hanscom, 2006). In this thesis we focus on pavement markings which are primarily qualified as perceptual countermeasures (PCM), meaning they are intended to regulate driving behavior mostly by manipulating the visual driving scene, but sometimes also by means of additional auditory and/or tactile feedback (Godley, 1999). The impression of increased motion is often generated optically by means of a sequence of transverse colored lines at decreasing distances apart in the travel direction, thereby stimulating drivers to slow down while approaching a dangerous road section. In case of so-called **transverse rumble strips** (TRS), this optical effect is accompanied by auditory and tactile feedback to drivers (Godley, 1999). In addition, optical lane narrowing illusions can serve both purposes of speed reduction and lateral control and are induced by other pavement markings, such as chevron and **herringbone patterns** (HP) (Godley, 1999).

In total, five driving simulator studies were performed in order to investigate the following main **research questions**:

1. Can we obtain a desired behavioral adaptation contributive to road safety in distance (along the road) by means of traffic calming measures?
2. With respect to distance along the road: Is there a difference between the different traffic calming measures in terms of the extent to which they contribute to a desired behavioral adaptation supporting road safety?
3. With respect to time (i.e., under repeated exposure during 5 consecutive days): Does the repeated exposure to the traffic calming measures have an influence on driving behavior near transitions or discontinuities?

Figure 17 provides a visual overview of the link between the specific TCMs under investigation and the three research questions.

The first research question is based on the fact that several field experiments and driving simulator experiments established that the influence of infrastructural measures (such as TCM) was limited in distance along the road. As an example, the results of Dixon et al. (2008) and Galante et al. (2010) indicate that the established speed reductions do not consistently extend beyond the vicinity (300 to 400 m) of the TCM. In their field experiment, Walter and Broughton (2011) found that the speed reduction effect was limited to 400 m after the digital information display. Furthermore, Santiago-Chaparro et al (2012) found that drivers started to increase their speed 90-150 m after the speed feedback sign. Based on this previous research, the first research question is investigated.

Within each of the five driving simulator studies, a comparison between the different design conditions was analyzed. Besides the specific traffic calming measure(s) under investigation, a control condition as baseline was also included. A mutual comparison of all these conditions can give more insight in differences and similarities in the associated driving behavior. The second research question focusses on this comparison.

The third research question originates in the diminishing effects of TCM on speed reductions under repeated exposure (e.g., Hallmark et al., 2007; S. Jamson & Lai, 2011). Two longitudinal driving simulator studies were performed in which participants were repeatedly exposed (during five successive days) to a gate construction at the rural-to-urban transition on the one hand and to the transversal rumble strips located at the tangent before a dangerous curve on the other hand.

Based on the results of the different driving simulator experiments, several recommendations can be given which can support road agencies and road designers to make their design safer and support the Safe System Approach.

Before the different studies are described in detail, a short introduction to driving simulator research in general in provided in Chapter 2. In addition, Ariën et al. (2015) (paragraph 2.4) elaborates in detail about the processing of driving simulator data before the statistical analysis takes place.

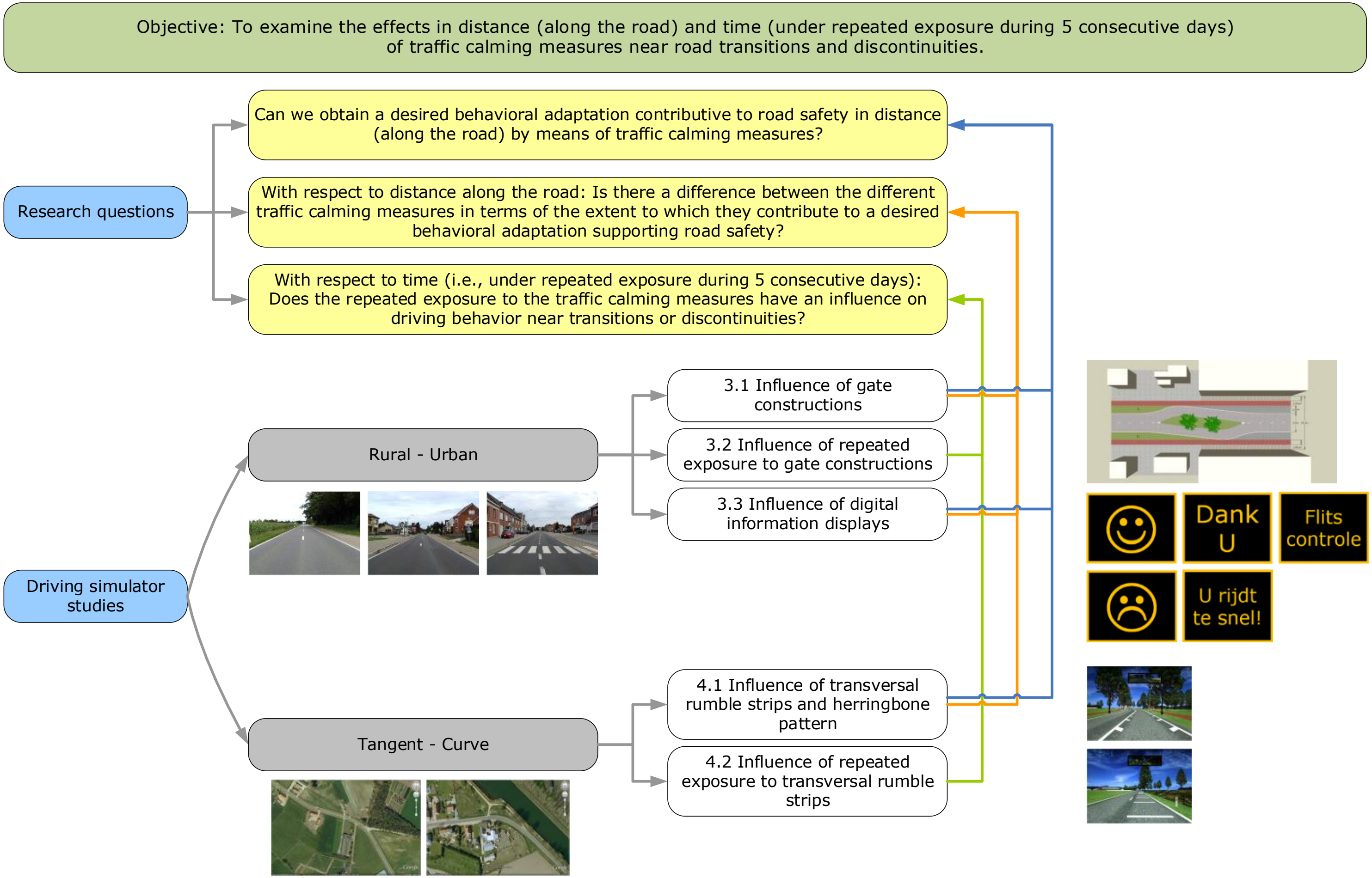


Figure 17 Overview of the link between the specific TCM under investigation and the three research questions

Chapter 2

METHODOLOGICAL PARADIGM – DRIVING SIMULATOR RESEARCH

2.1 INTRODUCTION TO DRIVING SIMULATOR RESEARCH

In order to examine the potential of different TCM nearby transitions and discontinuities and to investigate the research questions described in paragraph 1.5, five driving simulator studies were executed.

In driving simulator studies, participants are seated in a mock-up and navigate through a virtual road environment projected on a screen. Low-level simulators have a fixed mock-up and use one or more computer screens for scenario visualization. High-level simulators are more advanced and use a mock-up mounted on a moving base platform and virtual projection on large screens (e.g. 180° to 360°) (Fisher, Rizzo, Caird, & Lee, 2011). A virtual road environment is created, containing particular scenes of interest with particular traffic signs. The driving simulator logs detailed information about a large number of driving behavior parameters, including speed, acceleration, gear use, lane position, etc. Driving simulators can be combined with additional measurement systems such as an eye tracking system to synchronically log visual behavior or electroencephalography (EEG) monitoring to record electrical activity of the brain.

Interestingly, leading institutions and organizations worldwide such as The Transportation Research Board, indicate that recent innovations in computerized design assistance tools and techniques should be used to improve the understanding of how road geometry and infrastructural-related aspects (including positioning and design of traffic signs) affect traffic safety and operation (Transportation Research Board, 2007). In the context of road design, driving simulators are used to test driving behavior and approve new infrastructural features on the one hand and to visualize and experience design alternatives on the other hand (Bella, 2009; Keith et al., 2005). Besides the high level of detail of the collected driving data, other important advantages are the experimenter being in control over the road infrastructure and environment, thereby included the interaction with other (virtual) road users, and the guaranteed safety for road users (Godley, Triggs, & Fildes, 2002). Recently, virtual driving simulator environments which combine the manipulation of different participants at the same time (e.g., a car simulator combined with a bicycle simulator) are implemented ('A look inside Oregon State's bicycling and driving simulator laboratory', 2011).

A major issue is the extent to which behavior in the simulated environment corresponds to participants' actual driving behavior in a real-life environment (Fisher et al., 2011). Törnros (1998; in Godley, 1999) stated that relative validity is necessary in a driving simulator study whereas absolute validity is not essential.

Several experiments show that driving simulators generally reach high relative validity (i.e., mutually comparing different scenarios in the driving simulator) (e.g., Bella, 2009; Godley et al., 2002; Törnros, 1998; Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008a).

The realism of a driving simulator scenario can be improved by replicating as exactly as possible the scenario from existing road environments (e.g., experiments described in paragraph 3.3, 4.1 and 4.2, Bella, 2005; Yan et al., 2008a), or from road plans (e.g., Santiago-Chaparro et al., 2012). However, even in high-fidelity driving simulators, there are limits to the visual realism that can be offered (Bella, 2009; Bella, Garcia, Solves, & Romero, 2007; Klee, Bauer, Radwan, & Al-Deek, 1999), which is an important limitation compared to on-field studies and applications using video footage (De Ceunynck et al., 2015). In addition, there is a risk of participant drop-out due to simulator sickness.

An overview of the most important advantages and disadvantages of driving simulator studies is described by Fisher et al. (2011) (see Table 3).

Table 3 Advantages and disadvantages of driving simulators using virtual simulations (Fisher et al., 2011, pp. 5–4)

Advantage	**Disadvantage**
- Has the capability to place drivers into crash likely situations without harming them, such as when they are using drugs, fatigued, engaging in police pursuits, during extreme weather, using new technologies, among other dangerous activities.	- Simulated crashes do not have the same consequences as a real crash and may effect subsequent behavior. Crashes in a simulator may have an unknown psychological impact on participants.
- Many confounding variables that occur in on-road driving can be controlled when driving simulation is used (e.g., weather, traffic, lighting, frequency of vulnerable road users, wind, potholes, proportion of vehicle types, irrational or unexpected behavior of other drivers, and so forth).	- These confounding or interacting variables that occur in the real world also need to be understood and, since they cannot be fully recreated in simulators, are not necessarily amenable to testing (as yet). In other words, understanding driver behavior is in the interacting details.
- All of the sensory details of the real world are not used by drivers anyway. Perceptual information (Gibson, 1986) for driving is knowable and can be faithfully reproduced using simulators.	- The real world can never be perfectly reproduced (for now). The important combinations of real-world information and feedback that are important to driving are not completely known.
- Events or scenarios can be identically repeated for each participant.	- Each exposure or trial affects responses to subsequent exposures.
- Simulators offer cost savings through flexible configurability so that a wide range of research questions can be addressed.	- High-end simulators, such as NADs, require considerable hardware and software development to address a limited number of research questions.
- Even low-cost, low-fidelity simulators in the right hands can address a wide variety of interesting research questions.	- Low-cost simulators can be imprecise and inflexible and therefore do not address all needs.
- Driving simulation is compelling and elicits emotional reactions from drivers that are similar to those of actual driving.	- Drivers do not believe in the authenticity of the simulation at a fundamental level and responses are based on the perception.
- Simulators are good at assessing driving performance or what a driver can do (Evans, 2004).	- Simulator are not able to address questions of driver behavior, which is what a driver does do in their own vehicle.
- A structured driving training curricula can be set up and run for new drivers and for some skills, transfers to the open road.	- The extent that the driver training transfers to on-road skills is not known not is the relative cost-effectiveness of such programs.

2.2 DRIVING SIMULATOR OF THE TRANSPORTATION RESEARCH INSTITUTE – HASSELT UNIVERSITY

The driving simulator of the Transportation Research Institute – Hasselt University (Belgium) was used in all the five experiments. The medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated) is a fixed-base (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator (see Figure 18). The simulation includes vehicle dynamics, visual and auditory feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images and depiction of the speedometer. Three projectors offer a resolution of 1024 x 768 pixels and a 60 Hz refresh rate. The sounds of traffic in the environment and of the participant's car were presented. Data were collected at a 60 Hz frame rate.

Figure 18 Medium-fidelity driving simulator at the Transportation Research Institute – Hasselt University

Lee et al. (2011) propose several simulator features which are required to evaluate road design issues (see Table 4). A comparison with the characteristics of the medium-fidelity driving simulator of the Transportation Research Institute – Hasselt University shows that this simulator is a good match for the specified research questions and experiments.

Table 4 Matching simulator characteristics and simulator types to design issues (J. D. Lee et al., 2011, p. 57)

	Simulator characteristics							**Simulator types**			
Design issue	**Display resolution**	**Field of view / mirror**	**Cab realism**	**Control input**	**Auditory cues**	**Vehicle dynamics**	**Motion and vibration**	**Desktop**	**Low-fidelity**	**Medium-fidelity**	**High-fidelity**
Suitable sign placement and content	●	◎						Possibly effective[a]	Possibly effective[a]	Effective	Inefficient[c]
Lane or path selection (e.g., through roundabout, intersections, etc.	◎	●	◎	●		●		Possibly effective[b]	Possibly effective[b]	Effective	Effective
Driver reactions and responses to jersey barriers, columns, barrels, TCDs, lane width, lane shift, taper	●	○		●	○	●	○	Possibly effective	Effective	Effective	Inefficient
Driver behavior on work zone approaches (speed compliance and lane selection)	●	○		●	○	●	○	Possibly effective	Effective	Effective	Inefficient
Driver behavior at large, complex arterial intersection configurations (e.g., gap acceptance, dilemma zone)	●	●	◎	●	○	●	◎	Not effective	Possibly effective	Effective	Effective
Effects of roadway features (e.g., geometric design, driveway, curves, etc.) on driver speed	◎	●	◎	●	○	●	◎	Not effective	Possibly effective[b]	Effective	Effective

Note: Blank = no importance; ○ = low importance; ◎ = moderate importance; ● = high importance

[a] Dependent on display resolution

[b] Dependent on field of view

[c] Capabilities far exceed what is required. Method represents inefficient use of resources

2.3 MULTI-DIMENSIONAL APPROACH OF DRIVING BEHAVIOR

This thesis hinges upon the idea that drivers' behavior should be approached as a multi-dimensional, rather than a single-dimensional concept, i.e., as the combination of both longitudinal and lateral driving parameters (Rosey, Auberlet, Bertrand, & Plainchault, 2008).

The longitudinal dimension mostly applies to the way in which drivers manage their speed. Among the different speed-related parameters known in the literature, mean speed is very often used as measure for safe driving, mainly because elevated crash risk and severity have been related to an increase in mean speed (Safetynet, 2009b; European Commission, 1999; Shinar, 2007). Besides mean speed, standard deviation of longitudinal acceleration and deceleration (SDAD) is a popular parameter since it indicates the degree to which drivers are able to keep *variations* in speed under control. In addition, mean longitudinal acceleration and deceleration (mean acc/dec) is an interesting driving parameter because fluctuations in acc/dec indicate (large) changes in speed and can cause discomfort. Large mean acc/dec increases the risk for skidding accidents because of reduced tire-road surface friction (PIARC, 2003). When drivers abruptly change their speed, the homogeneity of the traffic flow is disrupted and the time to anticipate and/or react decreases. This might result in an increased risk for rear-end collisions (Dewar & Olson, 2007; Marchesini & Weijermars, 2010).

The lateral dimension of driving behavior relates more to managing the vehicle's horizontal position within the driving lane. Lack of a harmonized lane position is one of the primary factors in single-vehicle run-off the road and head-on collisions (Rosey et al., 2008). Mean values for lateral position are frequently used as indicators for lateral control (Auberlet et al., 2012; Bella, 2013; Charlton, 2007; Coutton-Jean, Mestre, Goulon, & Bootsma, 2009; Räsänen, 2005; Rossi et al., 2013a). In addition, the variation or standard deviation of lateral position (SDLP) is very often used in the literature as an indicator for lateral trajectory control. In addition, SDLP is a sensitive measure of driver impairment for example due to increased mental workload and various drugs (De Waard, 1996; Ramaekers, 2003).

By investigating both the longitudinal and lateral dimensions of driving behavior, this thesis will come to a multidimensional evaluation of different TCM. Before the detailed results of the different driving simulator studies are described, paragraph 2.4 describes the processing of driving simulator data before the statistical analysis takes place.

2.4 Processing driving simulator data before statistical analysis by means of interpolation and an integral formula

This chapter is based on:

Ariën, C.; Vanroelen, G.; Brijs, K.; Jongen, E.M.M.; Cornu, J.; Ross, V.; Mollu, K.; Daniels, S.; Brijs, T.; Wets, G. (n.d.) Processing driving simulator data before statistical analysis by means of interpolation and a simple integral formula. Submitted for first review in *Transportation Research part B* [web of science: 5 year impact factor 4.116].

Proceedings:

Ariën, C.; Vanroelen, G.; Brijs, K.; Jongen, E.M.M.; Cornu, J.; Daniels, S.; Brijs, T.; Wets, G. (2015) *Processing driving simulator data before statistical analysis by means of interpolation and a simple integral formula.* Processing driving simulator data before statistical analysis by means of interpolation and a simple integral formula. Presented at the 5th International Conference on Road Safety and Simulation, Orlando, USA.

Abstract

Driving simulator data can be sampled in function of distance or time. Distance sampling ensures that driving parameters are sampled at a constant distance interval. Time sampling ensures that driving parameters are sampled at a constant time interval. Importantly, when using time sampling, the distance interval is dependent on the driving speed, leading to a negative correlation between speed and number of sampled data points. The suitability of a sampling approach depends upon the envisaged type of analysis (i.e., point location based analysis vs. zonal-based analysis) and is illustrated by means of five driving simulator datasets from two driving simulator software packages.

The nearest sampled parameter value in the direct vicinity of the specific point is a very good proxy for the driving parameter value at the point of interest along the road (e.g., at curve entry, curve middle, and curve exit). The analysis of driving parameters in zones of a pre-specified length (e.g., mean speed in a zone of 50 m nearby an intersection) requires a different approach. Significant differences were discovered between mean parameter values based on raw sampled data on the one hand, and mean parameter values based on interpolated data on the other hand. More specifically, mean speed values were significantly underestimated by the raw sampled data in some zones as the result of large speed variations within the zone of interest. The typical differences ranged from 9% to 25%. The established differences in mean LP in this paper were negligible. To better understand how these differences emerge, we introduce an equivalent integral formula which shows that in a distance zone the mean value of a driving parameter with respect to distance can also be calculated as a quotient of two averages from a time perspective.

In summary, the interpolation technique and the alternative formulas are preferred over using raw sampled data to calculate mean parameter values. Based on this paper, we would like to demonstrate that it is very important to mention the data processing approach in the driving simulator methodology.

Highlights

- Driving simulator data can be sampled in function of distance or time
- Nearest sampled parameter value is a good proxy for the value at a point
- Speed variations in zones result in mean speed underestimations based on raw data
- Interpolated data are more suitable for the analysis of driving parameters in zones
- Describing data processing approach is important in driving simulator research

2.4.1 Introduction

Driving simulators are used to gain insight into a variety of research topics such as fitness-to-drive, the impact of new in-vehicle technologies, educative and training programs, and applications of different geometric design principles (Blana, 1996; Fisher et al., 2011). Several studies have repeatedly proven that driving simulator research has several advantages. It is safe, cost efficient and provides researchers with total control over various driving conditions and with a continuous high rate data collection (Charlton, 2007; Kaptein, Theeuwes, & van der Horst, 1996; L. Nilsson, 1993; Rudin-Brown, Williamson, & Lenné, 2009).

In order to get insight in the multi-dimensional aspects of driver behavior, both longitudinal and lateral control are of interest in driving simulator research (Rosey et al., 2008 and see paragraph 2.3). The driver's speed management relates to the longitudinal dimension. In the literature, mean speed is the very often used measure for safe driving because it is related to crash risk and severity (European Commission, 1999; Safetynet, 2009b; Shinar, 2007). Another popular speed-related parameter is the standard deviation of longitudinal acceleration and deceleration because it indicates the degree to which a driver is able to control variations in his speed. When drivers abruptly change their speed, the homogeneity of the traffic flow is disrupted and the time to anticipate and/or to react decreases, which might result in an increased risk for rear-end accidents (Marchesini & Weijermars, 2010). The lateral dimension on the other hand relates to the driver's management of the vehicle's horizontal position within the driving lane. Single-vehicle run-off the road and head-on collisions are often related to a lack of a harmonized lane position (Rosey et al., 2008). Lateral trajectory control is often measured by the variation or standard deviation of lateral position (SDLP). This parameter is a known indicator for driver impairment, for example due to various drugs or mental workload (de Waard, 1996; Ramaekers, 2003).

In this paper, we present a short overview of data sampling and analysis methods for processing driving simulator data which is to be carried out prior to statistical analysis. First, we make a distinction between distance sampling and time sampling and relate these sampling methods to point location based analysis and zonal-based analysis. We will indicate some difficulties may arise in calculating parameter values for a specific point location or zones of interest. To address this issue, we present a piecewise polynomial interpolation technique and introduce a simple integral formula which makes the interpolation technique redundant for calculating mean parameter values. Finally, we illustrate the interpolation technique and the formula by means of five driving simulator datasets from two different driving simulator software packages (i.e., STISIM M400 and NADS MiniSim™) that were previously collected for experiments conducted at our research institute (i.e., Transportation Research Institute (IMOB) of Hasselt University).

2.4.2 Data sampling and analysis methods

A. Data sampling approach

While participants are driving, simulator driving performance data can be sampled in function of distance or time. **Distance sampling** ensures that driving parameters are sampled at a constant distance interval (e.g., every 2 meters). **Time sampling** on the other hand ensures that driving parameters are sampled at a constant time interval (e.g., every 14 milliseconds) with time frequency usually set between 30 and 240 Hz (Fisher et al., 2011, pp. 20–2). Importantly, when using time sampling the distance interval is dependent on the driving speed, leading to a negative correlation between the driver's speed and the number of sampled data points.

This negative correlation is illustrated in Figure 19 and the equation below. Each point in the graph represents the number of sampled data points for a specific subject and its mean driving speed on a 50 m road stretch. This data belongs to dataset 1 which is described hereafter in this paper.

Figure 19 shows that the number of sampled data points (n_d) on a specified road stretch (Δd) increases when the subjects' mean driving speed ($\bar{v}$) on that road stretch decreases. Starting from the mechanical formula for mean speed where the travelled distance is divided by the elapsed time (formula 1), the number of sampled data points is equal to formula 2. The frequency rate (f) is equal to 1 divided by the time interval between two sampling points (*timestep*).

$$\bar{v} = \frac{\Delta d}{\Delta t} = \frac{\Delta d}{n_d \cdot timestep} = \frac{\Delta d \cdot f}{n_d} \qquad (1)$$

$$n_d = \frac{\Delta d \cdot f}{\bar{v}} \qquad (2)$$

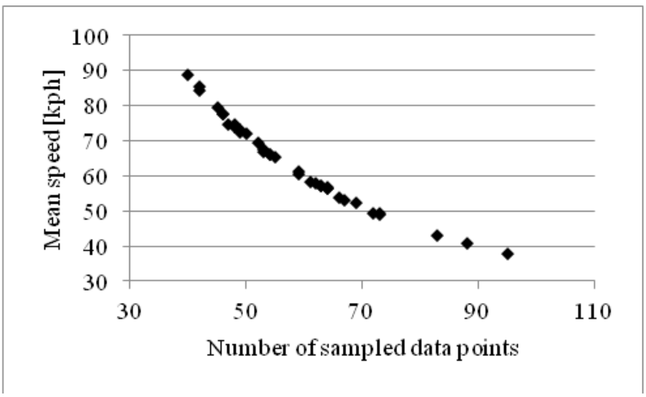


Figure 19 Inverse relationship between driver's speed and the number of sampled data points

Although there are important differences between both sampling methods (see next paragraph), the method used is hardly ever mentioned in driving simulator research papers. To the best of our knowledge, there are only a handful of simulator experiments reporting the sampling method (and frequency rate). As an example, in this thesis data is collected data a 60 Hz frequency rate while Montella et al. (2013) used a 20 Hz frequency rate and Cantin, Lavallière, Simoneau and Teasdale (2009) applied a sampling rate which varied with the speed of rendering of graphics (from 20 to 30 Hz). In this paper we elaborate more precisely on the advantages and disadvantages of both sampling approaches as well as on their applicability.

B. Point location based analysis versus zonal-based analysis

The suitability of the distance or time sampling approaches is dependent upon the envisaged type of analysis, which in turn is determined by the underlying research question. Two analysis types are distinguished: a point location based analysis and a zonal-based analysis. Both analysis types are illustrated by means of a case for a curve, an intersection and a hazard situation in Figure 20.

In the **point location based analysis**, the researcher is interested in drivers' behavior at a series of specifically located points along the road. As an example, Charlton (2004, 2007) analyzed mean speed and mean lateral position at several specific points along a curve section (ex. 100 m before curve, 50 m before curve, at curve entry, curve middle, curve end and 50 m after curve) in order to investigate the effect of curve treatments on driving behavior. Studies investigating driving behavior nearby intersections are, for instance, interested in driving speed at the onset of a yellow signal (Yan, Radwan, Guo, & Richards, 2009).

By means of the **zonal-based analysis**, researchers can investigate the average (mean), variance (standard deviation), minimum or maximum of driving behavior parameters along a road segment. For instance, Comte and Jamson (2000) and Jamson and Merat (2007) applied this zonal-based analysis nearby curves and variable message signs and examined driving behavior in zones of respectively 30 m and 250 to 500 m. Abbas, Machiani, Garvey, Farkas and Lord-Attivor (2014) analyzed mean speed on a road stretch between the onset of yellow and the stopping point in order to investigate the stopping process. Finally, the approach of the hazard situations in the study of Crundall and colleagues (David Crundall et al., 2012; David Crundall, Andrews, van Loon, & Chapman, 2010) was subdivided into 10 zones of 10 m in order to "display the sensitivities of drivers to hazards" (David Crundall et al., 2010, p. 2120).

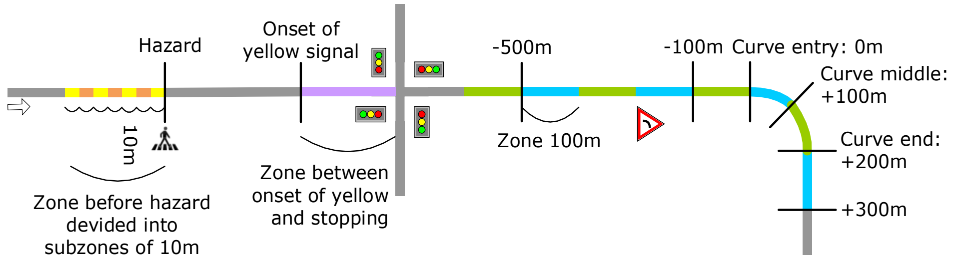


Figure 20 Illustration of point location based analysis (black lines) and zonal-based analysis for a hazard (yellow and orange zones), an intersection case (purple zone) and a curve (green and blue zones)

C. Interpolation technique for point location based analysis

Concerning the point location based analysis, distance sampling seems more appropriate than time sampling because the simulator directly captures data at a constant distance interval. A remaining issue however is that a predetermined distance interval might not correspond to the specific point location of interest. As an example, the predefined distance interval of 2 m does not provide data for point locations at uneven distance positions. Time sampling on the other hand produces a dataset with parameter values at random point locations because the sampling interval depends on the driver's speed and does not provide the parameter values at the specific points of interest.

To summarize, neither distance sampling nor time sampling provide fully accurate estimation of the driving parameter value at specific points of interest. In order to solve the mismatch between the position of the sampled data and the position of interest, a couple of approaches can be suggested to determine the best estimation for the parameter value at the position of interest. The first approach assumes that the **parameter value of the nearest point location** is the best estimation for the parameter value at the point location of interest. However, this approach might over- or underestimate the actual parameter value, particularly on road segments with high driving speeds (such as on a motorway) because the distance between the specific point of interest and the nearest point might be relatively large, especially in case of small time sampling frequency rates.

Another approach is the **piecewise linear interpolation technique** that allows to transform both time and distance sampling to the preferred data points. In general, interpolation allows to obtain a good approximate value of a driving parameter P when there is no sampled data available at a certain point U. Piecewise linear interpolation provides reliable results in many cases. For this technique, the first step is to find the parameter values at the nearest points before (U_b) and after (U_e) the point of interest, resulting in parameter value P_b and P_e. Then, both data pairs are connected with a straight line in order to obtain a linear interpolation value P_i as an approximate value for P. Calling these nearest data pairs respectively (U_b, P_b) and (U_e, P_e), the following formula for P_i at a certain point U can be proposed:

$$P_i = P_b + \frac{P_e - P_b}{U_e - U_b}(U - U_b) \qquad (3)$$

If the software supports this technique, it is also possible to use a more advanced piecewise interpolation approach like cubic spline interpolation. Here, the nearest points are connected with an appropriate third-degree polynomial so that the interpolation curve looks smoother than in case of a straight line. Yet, if the sampling frequency of the simulator is higher than 20 Hz, the spline technique is of no added value since the respective interpolation values will hardly differ from one other. More information about the interpolation technique can be found in for instance Moler (2004).

A final important constraint is that the interpolation technique performed on a (U, P)-dataset requires that all U-values are different from each other. In case of time sampling, the nearest sampled data pair is certainly not unique when the car drives slowly. In that situation, one has to decide which driving parameter value to choose to successfully run the interpolation algorithm. In circumstances such as these, we took the smallest parameter value belonging to a certain point *U in order make sure that the slowest speeds were incorporated in the final analyses*.

Both the nearest value approach and the piecewise linear interpolation technique will be illustrated by means of a driving simulator (i.e., STISIM-M400 system) dataset that was collected for an experiment in which driving behavior in and nearby a dangerous curve was investigated (see dataset 1).

D. Interpolation technique and formulas for zonal-based analysis

The situation is different if one is interested in analyzing driving parameters in zones of a pre-specified length (for example: mean speed or mean lateral position in a zone of 100 m nearby a dangerous curve) (see Figure 20), rather than at specific point locations. The advantage of distance sampling is that the same number of parameter observations is recorded for all drivers, even if between-subject speed differs or individual driving speed varies in the zone of interest. The problem however is that the predefined distance interval might not coincide with the borders of the zone of interest.

For time sampling, the biggest concern is the generation of potentially inaccurate parameter values since within- and between-subject variance in speed results in a different number of parameter observations for the zone of interest (remember the negative correlation between the driver's speed and the number of sample data points for time sampling; see Figure 19). When calculating the mean or standard deviation for the driving performance parameter in that zone, parameter values at a subzone (i.e., segment within the zone of interest) with a lower driving speed weigh more in the calculation than parameter values at a higher driving speed segment. This in turn, might result in an inaccurate parameter value in the zone of interest.

We visualize this in Figure 21 by means of dataset 2 (for more information on dataset 2, see paragraph 2.4.3 D). Both panels show subjects' individual driving speed on the y-axis. The x-axis of the left graph represents the elapsed time during the last 50 m before subjects come to a stop in front of an intersection where lights switched from green to yellow and red. Due to the different driving speeds for the different subjects, longer elapsed times (and thus more parameter values) are sampled for drivers who drive slower. The same 50 m distance interval is presented on the x-axis of the right graph. The plotted lines are exactly 50 m long for each subject but vary in terms of start- and/or endpoint in function of when and how more precisely subjects initiate and complete their stop. The black vertical line represents the stopping line at the intersection. When calculating the mean driving speed of the blue subject based on the time sampling approach, mean speed is equal to 25.5 kph. Different from that, the right graph indicates a mean speed of 39 kph. The underestimation of the mean driving speed based on the left graph is the result of the overrepresentation of the lower driving speeds. Indeed, from a time sampling point of view, more speed parameter values are sampled in the time period where subjects drive slowly. For other driving parameters like acceleration/deceleration and lateral position, an overestimation is also possible when these parameter values are higher in the subzone where driving speed is lower compared to the subzone where driving speed is higher.

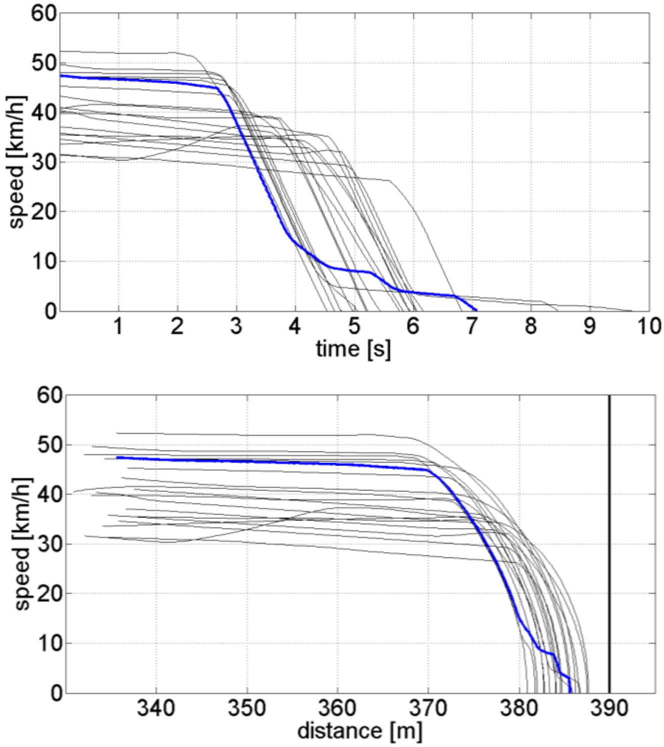


Figure 21 Individual driving speeds visualized by means of a time (left) and distance (right) approach

In sum, neither distance sampling nor time sampling provide the preferred raw data to calculate the parameter value in a zone. Hereafter, we propose some methods to solve this problem. In case the time and distance at the beginning and end of the analysis zone are available (by means of point location based analysis), mean speed can be calculated by dividing the travelled distance by the elapsed time. This equation represents the basic mechanical formula for speed but is not applicable to other driving parameters like mean or standard deviation of lateral position. The **interpolation technique** (cf. paragraph 2.4.2 C) is a suitable approach for the analysis of all kinds of driving parameters. Based on the interpolation technique, the parameter values at points located at predefined constant distance intervals can be estimated. Because the distance interval between two parameter values is constant, and thus independent of the subject's driving speed, the same number of parameter values is available for each subject in the zone of interest. Therefore, the calculated mean or standard deviation of the parameter values in the zone of interest will not be an under- or overestimation of the correct result.

For the zonal-based analysis, application of the piecewise interpolation technique on a set of equidistant points requires the specification of a step size. A good rule of thumb is to choose a step size for which the number of created interpolated points is in line with the number of sampled data point in that zone. When the step size results in a significant lower number of interpolated data point compared to the number of sampled data, a serious aggregation of the data takes place and specific details in the data will get lost.

The previous considerations show that there are two possible ways to determine the average of a driving parameter. A first approach is to calculate the average of all sampled parameter values that are available for every subject in a specific time interval (corresponding to the distance zone of interest). We refer to this mean value as $\overline{P_T}$. However, as described above, it could be more appropriate to calculate the average of all interpolated parameter values with respect to this distance zone (DZ), notation: $\overline{P_{DZ}}$. According to the first mean value theorem for integration (Briggs & Cochran, 2011), it is possible to rewrite both mean values as the outcome of a definite integral divided by the length of the respective time (ΔT), or distance interval (ΔD). More specifically, assuming that we have a smooth underlying parameter curve $p(\cdot)$, the formula will look like:

$$\overline{P_T} = \frac{\int_{(T)} P \cdot dt}{\Delta T} \tag{4}$$

$$\overline{P_{DZ}} = \frac{\int_{(DZ)} P \cdot dx}{\Delta D} \tag{5}$$

Consequently, from a numerical point of view, it is possible to estimate formula 5 more accurately than by simply applying the classical formula for calculating the average. Therefore, in our specific cases we will use the following adjusted formula. This formula is based on the so-called trapezoidal rule (Moler, 2004) in numerical analysis and counts only half of the sampled parameter values at the edge of the distance zone in order to get a more precise estimation of the mean driving parameter value.

$$\overline{P_{DZ}} = \frac{\int_{(DZ)} P \cdot dx}{\Delta D} \cong \frac{\frac{P_0}{2} + P_1 + P_2 + \cdots + P_{n-1} + \frac{P_n}{2}}{n} \tag{6}$$

As we already mentioned in the beginning of this section and illustrated in Figure 21, the difference between $\overline{P_T}$ and $\overline{P_{DZ}}$ could be large. To better understand how this difference emerges, we transform the integral formula for $\overline{p_{DZ}}$ to an integral with respect to the time. This results in the following formula:

$$\overline{P_{DZ}} = \frac{\int_{(DZ)} P \cdot \frac{dx}{dt} \cdot dt}{\Delta D} = \frac{\int_{(T)} P \cdot v \cdot dt}{\int_{(T)} v \cdot dt} = \frac{\overline{(P \cdot v)_T}}{\overline{v_T}} \tag{7}$$

Note that, in this derivation, we use a well-known result from mechanics, namely, that 'distance travelled is equal to the integral of the speed function' (Hibbeler, 2013). Formula 7 shows that in a distance zone the mean value of a driving parameter with respect to distance can also be calculated as a quotient of two averages from a time perspective. For this purpose, one needs to multiply the sampled parameter and speed values with each other and then calculate the (time) average. As a result, the two averages $\overline{P_T}$ and $\overline{P_{DZ}}$ are only equal when $\overline{(P \cdot v)_T} = \overline{P_T} \cdot \overline{v_T}$, which is only possible when the sampled parametric values remain constant on the distance zone of interest. The downside to this formula is that the average $\overline{(P \cdot v)_T}$ has only limited relevance in a driving context. However, there is one specific case in which this formula can be further adapted, namely, if the parameter *P* is equal to the speed *v* itself. Then, we can posit the following:

$$\overline{v_{DZ}} = \frac{\int_{(T)} v^2 \cdot dt}{\int_{(T)} v \cdot dt} = \frac{(\overline{v_T})^2 + \frac{\int_{(T)} (v - \overline{v_T})^2 \cdot dt}{\Delta t}}{\overline{v_T}} = \overline{v_T} \cdot \left(1 + \left(\frac{\sigma_{v,T}}{\overline{v_T}}\right)^2\right) \qquad (8)$$

In formula 8 we recognize the so-called coefficient of variation ($\frac{\sigma_{v,T}}{\overline{v_T}}$) (Triola, 2014). Based on this, we learn that the value of the average speed (calculated according to a distance perspective) will increase by a percentage equal to the square of the coefficient of variation (calculated from a time perspective). As a result, the biggest differences between the two approaches ($\overline{P_T}$ and $\overline{P_{DZ}}$) are expected when the speed variations ($\sigma_{v,T}$) in the zone of interest are the largest. For the sampled data however, this means that one could obtain a good estimate of $\overline{v_{DZ}}$ without performing the interpolation step. As a result, one only has to compute the coefficient of variation of all sampled speed values in the corresponding time interval.

2.4.3 Cases

In order to illustrate the differences between point location versus zonal-based analysis for parameter values based on time sampling, five datasets are analyzed. More in detail, we will use the raw data, the piecewise linear interpolation technique and the presented formulas. A summary of the five cases is presented in Table 5. The following paragraphs describe the data analysis, the driving simulator apparatus and the overview of the five cases. Since it is not the major purpose of this paper, we will not describe driving behavior in curves or nearby intersections and hazards in detail. Instead, we aim to illustrate the differences between the application of: (1) point location based analysis using the nearest point values or interpolated data and (2) zonal-based analysis using raw data, interpolated data (formula 6) or the simple integral formula approach (formula 8 for mean speed and formula 7 for mean lateral position). For these five cases we start from raw datasets based on time sampling.

Table 5 Summary of five cases

Case	Description scenario	n	Interpolation step size	Point location based analysis	Zonal-based analysis
1	Dangerous curve	32	1 m	2 (Approach) × 7 (Point) ANOVA for speed	3 (Approach) × 6 (Zone) ANOVA for mean speed and LP
2	Intersection equipped with red light camera and warning sign	19	0.5 m		3 (Approach) × 2 (Zone) ANOVA for mean speed and LP
3	Motorway exit followed by yield controlled intersection	29	1 m		3 (Approach) × # (Zone) ANOVA for mean speed # 1 x 1200 m 2 x 600 m 3 x 400 m 6 x 200 m 12 x 100 m 24 x 50 m
4	Hazard situation: 2 kids are going to cross the street at a zebra crossing. The kids are temporally hidden by trees.	40	0.5 m		3 (Approach) × 10 (Zone) ANOVA for mean speed and LP
5	Hazard situation: pedestrian at zebra crossing	28	1 m		3 (Approach) × 10 (Zone) ANOVA for mean speed and LP

A. Data analysis

Concerning the point location based analysis, driving speed is determined as the speed parameter value of the nearest point location, and as the interpolated value based on formula 3. Both approaches are statistically compared by means of a 2 (*Approach*: nearest value, interpolation) × # (*Point*) within-subject analysis of variance (ANOVA) for mean speed.

In addition to the point location based analysis, several zones are analyzed for mean speed and mean lateral position (LP) in the different cases. The mean speed value for each zone is determined by means of three different approaches:

A. Calculate mean speed based on all sampled speed values in the time interval that corresponds with the distance interval of interest (i.e., zones);
B. Calculate mean speed based on the interpolated values in a zone using formula 6 (the step size for interpolation is indicated in Table 5);
C. Calculate mean speed based on the coefficient of variation using formula 8.

A 3 (*Approach*) × # (*Zone*) ANOVA for mean speed was conducted to analyze the difference between the three approaches in the 6 zones of interest. The same ANOVA is performed for mean LP, however approach C used formula 7 instead of formula 8.

B. Driving simulator apparatus

All datasets were collected in driving simulators belonging to our research institute (i.e., the Transportation Research Institute (IMOB) of Hasselt University, Belgium). To illustrate the different analysis approaches in a variety of situations, different driving simulator mockups and two software packages were used.

All driving simulators were fixed-base (i.e., drivers do not receive kinetic feedback) with a force-feedback steering wheel, brake pedal and accelerator simulated vehicle dynamics and visual and auditory feedback. A variety of driving performance measures was collected at a frequency rate of 60 Hz, thus time sampling was used. A sound system provided the sound of traffic in the environment and the participant’s car. The characteristics of the different driving simulators are described in Table 6.

Table 6 Driving simulator characteristics

	Case	
1, 2, 3	4	5
	Software	
STISIM M400, version 2	STISIM M400, version 2	NADS MiniSim™ version 2.0
	Visualization	
180° seamless curved screen with 3 projectors offering a resolution of 1024 x 768 pixels and a 60 Hz refresh rate	3 LCD monitors (screen size in cm: 34 x 27) offering a resolution of 1024 x 768 pixels and a 60 Hz refresh rate	140° screen by means of tv screens offering a resolution of 4800 x 1024 pixels and a 60 Hz refresh rate
		

C. Dataset 1 – Dangerous curves

The first dataset relates to an experiment that investigated driving behavior in dangerous curves (Ariën et al., 2016 (paragraph 4.1)). This dataset is interesting because literature shows that driving behavior at both point locations and zones are relevant for road safety research (e.g. Charlton, 2004, 2007; Comte & Jamson, 2000; A. H. Jamson & Merat, 2007).

The driving scenarios consisted of a combination of several curve sections and filler pieces. The specific curve section which is further analyzed in this paper, was a 130 m long left-oriented compound curve preceded by a long tangent with a speed limit of 90 khp (i.e., curve location A in Ariën et al. (2016) (paragraph 4.1)).

Typically, researchers are interested in mean driving speed and SD of the lateral position nearby and inside curves. Some experiments used point location based values, for instance at curve entry, curve middle and curve end (e.g. Ariën et al., 2016 (paragraph 4.1); Charlton, 2004, 2007), while others analyze the mean or SD of parameter values in successive curve zones, for instance 30 m zones in the case of Comte and Jamson (2000). In light of these studies, we analyze driving speed at 7 point locations nearby and inside the curve. In addition to the point location based analysis, we analyze 6 zones for mean speed and mean lateral position (LP) (see Figure 22).

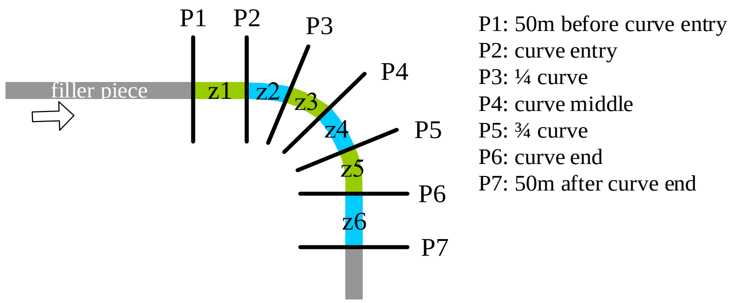


Figure 22 Visualization of 7 points and 6 zones nearby and in curve

D. Dataset 2 – Intersection equipped with red light camera and warning sign

The second dataset was collected in order to examine drivers' behavior nearby intersections equipped with traffic lights, red light cameras (RLC) and an additional warning sign (see Polders et al., 2015). The selection of this dataset was based on the fact that the variation in driving speed was large during the last road stretch before the vehicle stopped at the intersection. Based on formula 8 described in paragraph 2.4.2 D, we expect larger differences between mean speed values based on the raw sampled data and those based on the formula.

In the current paper, we limit our analysis to the driving simulator data from 19 subjects who stopped at the intersection equipped with a RLC and warning sign. The speed limit nearby the intersection was 50 kph and the signal light turned from green to yellow when participants were 2.5 sec away from the stop line.

Driving behavior nearby intersections equipped with traffic signs is examined in the literature by means of both point location based analysis (Yan et al., 2009) and zonal-based analysis (Abbas et al., 2014). Based on the fact that the variation in driving speed is large in the final road stretch before a subject stopped at the intersection for the yellow sign, we were interested in analyzing mean speed nearby the intersection. More in detail, we analyze mean speed over the final 50 m before the stop line (zone 1) and over the first 50 m after starting to drive again (zone 2). We calculate mean speed according to the three approaches for zonal-based analysis.

E. Dataset 3 – Motorway exit followed by yield controlled intersection

The third dataset comes from an experiment in which driving behavior was analyzed nearby and in different motorway exit designs (straight and curved) that were combined with different intersection types. In this study, we focus on the data of 29 participants who first completed a long stretch of 15 km motorway at 120 kph, and then took a curved motorway exit that ended in a yield controlled intersection where they had to turn to the right, entering a 70 kph secondary road.

In dataset 3 we detected a large variation in driving speed on the motorway exit before participants started slowing down (and in some cases stopped) at the intersection. Based on formula 8 described in section, we expect larger differences between mean speed values based on the raw sampled data and those based on the formula.

Compared to dataset 2, the motorway exit of 1200 m was split into different subzones (see Table 5), and mean speed was calculated for each subzone based on the three approaches. Based on the different subzones, we are able to examine the influence on mean speed of the subzone length and the location of this subzone with respect to the intersection.

F. Dataset 4 – Hazard situation: two children initially hidden by trees, at a zebra crossing

The fourth dataset relates to an experiment in which underlying cognitive mechanisms of hazard perception were investigated in young novice drivers (V. Ross, Jongen, Brijs, Brijs, & Wets, in preparation). More, specifically, it aimed to investigate the contribution of different working memory processes (i.e., ranging from simple information maintenance, to the updating and manipulation of information) to hazard perception abilities.

One specific hazard situation is selected, namely, a 30 kph zone with two children that are first hidden by trees and about to initiate crossing maneuver at a zebra crossing. The pedestrians start to cross when the driver is 80 m away from the pedestrians. The velocity of the pedestrians is based on the current driving speed when they start to walk. A pedestrian crossing sign combined with a 30 kph zone sign (i.e., 106 m away from the hazard) serve as precursors for the hazard.

The analysis method is based on previous research (David Crundall et al., 2010; V. Ross, Jongen, Vanvuchelen, et al., in preparation) where the environment immediately surrounding the hazard was divided in zones of 10 m, which allows detailed insights into the driving behavior nearby hazards. For the current paper, mean speed and mean LP will be determined in five subzones of 10 m before the hazard (zone 1-5) and five subzones of 10 m following the hazard (zone 6-10).

G. Dataset 5 – Hazard situation: pedestrian at zebra crossing

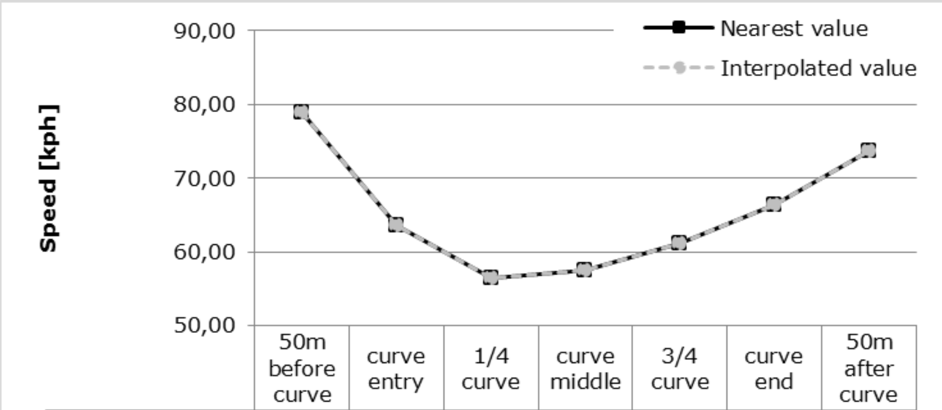
This particular dataset was collected in order to examine the effect of digital illuminated billboards (DIB) on driving behavior (see Mollu et al., 2016). A crossing pedestrian at a zebra crossing located in the transition zone between a rural (70 kph) and an urban environment (50 kph) and at 41 m or 65 m before the DIB, was introduced as manipulation condition. The pedestrian became visible at a time to collision of 4 s and had a crossing velocity of 4.8 kph. Accordingly, the driver was surprised when encountering the pedestrian and might have reacted differently with respect to the DIB. In this paper we focus on the mean speed in 10 zones of 50 m, where five zones were located before the zebra crossing (zone 1-5) and five zones were located after the zebra crossing (zone 6-10).

2.4.4 Results

In this section the results of the different ANOVAs are described. It is important to note that significant (interaction) effects were only of interest when the factor *Approach* was a significant (part of the interaction) effect since it is not the purpose of this paper to analyze or describe driving behavior in the curve or near the intersection or hazard situation. Rather we aim to illustrate the differences between the different approaches. Therefore, the results for the factor *Point* or *Zone* are not discussed. For all analyses, *p*-value was set at 0.05. ANOVAs were corrected for deviation from sphericity (Greenhouse-Geisser epsilon correction) and the corrected F-and probability values are mentioned.

A. Point-location bases analysis for speed based on dataset 1

Figure 23 shows the **speed** values at the 7 point locations according to the nearest value approach or the interpolation formula (3). The ANOVA for speed values at the 7 point locations showed no significant main ($F_{(1,\ 31)} < 1$, $p = 0.507$) or interaction effect ($F_{(3,96)} < 1$, $p = 0.673$) with the factor *Approach*. This indicates that there were no significant differences between the speed values based on the nearest value approach or based on the interpolated value.



	50m before curve	curve entry	1/4 curve	curve middle	3/4 curve	curve end	50m after curve
Nearest value	78,90	63,55	56,48	57,52	61,19	66,40	73,73
Interpolated value	78,92	63,55	56,47	57,53	61,19	66,40	73,73

Figure 23 Speed values at 7 point locations in curve (dataset 1)

B. Zonal-based analysis for mean speed based on dataset 1-5

Table 7 shows the results of the different ANOVAs for mean speed which were performed on the different datasets. Post-hoc pairwise comparisons were performed when the interaction effect *Approach* × *Zone* was significant. When mean driving speed in a specific zone was significantly different between the three approaches, the relative difference between the mean speeds is reported in percentages. When the relative speed differences between the different approaches were smaller than 2%, these were not reported in the table as they are considered as too small.

Table 7 Results of the ANOVAs for mean speed of the different datasets

Case	ANOVA	F	p	Zone	**Sampled ⇔ interpolated**	**Sampled ⇔ formula 8**	**Interpolated ⇔ formula 8**
1	*Zone*	29.2	<.0005	Relative differences between mean speeds based on the three approaches were smaller than 2% and are not further elaborated.			
	Approach	21.8	<.0005				
	Approach × Zone	6.2	0.04				
2	*Zone*	60.1	<.0005	Average of 50 m zone before and 50 m zone after intersection	26.2 ⇔ 32.8 25%	26.2 ⇔ 32.8 25%	32.8 ⇔ 32.8 < 1%
	Approach	124.5	<.0005				
	Approach × Zone	4.0	0.061				
3	*Approach (1 x 1200 m)*	288.3	<.0005	Average of 1200 m motorway exit	67.9 ⇔ 73.7 9%	67.9 ⇔ 73.7 9%	73.7 ⇔ 73.7 < 1%
	Zone (2 x 600 m)	130.6	<.0005	Zone 2: last 600 m before intersection	60.1 ⇔ 66.0 10%	60.1 ⇔ 66.1 10%	66.0 ⇔ 66.1 < 1%
	Approach	172.0	<.0005				
	Approach × Zone	102.2	<.0005				
	Zone (3 x 400 m)	147.2	<.0005	Zone 3: last 400 m before intersection	55.5 ⇔ 62.7 13%	55.5 ⇔ 62.8 13%	62.7 ⇔ 62.8 < 1%
	Approach	111.4	<.0005				
	Approach × Zone	70.5	<.0005				
	Zone (6 x 200 m)	121.7	<.0005	Zone 6: last 200 m before intersection	45.0 ⇔ 51.6 15%	45.0 ⇔ 51.7 15%	51.6 ⇔ 51.7 < 1%
	Approach	151.8	<.0005				
	Approach × Zone	104.2	<.0005				
	Zone (12 x 100 m)	115.9	<.0005	Zone 12: last 100 m before intersection	35.2 ⇔ 38.7 10%	35.2 ⇔ 38.6 10%	38.7 ⇔ 38.6 < 1%
	Approach	71.0	<.0005				
	Approach × Zone	21.8	<.0005				
	Zone (24 x 50 m)	107.0	<.0005	Zone 24: last 50 m before intersection	29.8 ⇔ 32.6 9%	29.8 ⇔ 32.5 9%	32.6 ⇔ 32.5 < 1%
	Approach	55.5	<.0005				
	Approach × Zone	16.4	<.0005				
4	*Zone*	109.3	<.0005	Zone 4: between 20 and 10 m before hazard	14.0 ⇔ 17.4 25%	14.0 ⇔ 17.5 25%	17.4 ⇔ 17.5 < 1%
	Approach	93.8	<.0005				
	Approach × Zone	19.4	<.0005	Zone 5: between 10 and 0 m before hazard	13.6 ⇔ 15.8 17%	13.6 ⇔ 15.8 17%	15.8 ⇔ 15.8 < 1%
5	*Zone*	361.3	<.0005	Zone 5: between 50 and 0 m before hazard	19.9 ⇔ 39.2 97%	19.9 ⇔ 39.2 97%	39.2 ⇔ 39.2 < 1%
	Approach	334.1	<.0005				
	Approach × Zone	325.6	<.0005	Zone 6: between 0 and 50 m after hazard	34.0 ⇔ 34.9 3%	34.0 ⇔ 34.9 3%	34.9 ⇔ 34.9 < 1%

Although the ANOVA for **dataset 1** contained a significant interaction effect *Approach* × *Zone*, the pairwise comparisons showed no important differences in mean speed between the three approaches when driving through a dangerous curve.

When we consider mean driving speed nearby intersections (dataset 2 and 3), the interaction *Approach* × *Zone* was (marginally) significant. The pairwise comparisons between the three approaches showed significant differences in mean speed. In the two zones of 50 m around the intersection in **dataset 2** the mean driving speed calculated by means of the sampled data (A) (26.2 kph) was significantly lower compared to both the mean speed based on interpolated data (B) (32.8 kph) and formula 8 (C) (32.8 kph). As a result, the mean speed based on the sampled data underestimated the mean speed by 25%, compared to the interpolation approach and formula 8. Figure 24 visualizes the speed of the individual drivers by means of a time (upper graphs) and distance (lower graphs) approach for the 50 m zone before stopping (left graphs) and 50 m zones after stopping (right graphs). For a detailed interpretation of these graphs, we refer to the description of Figure 21.

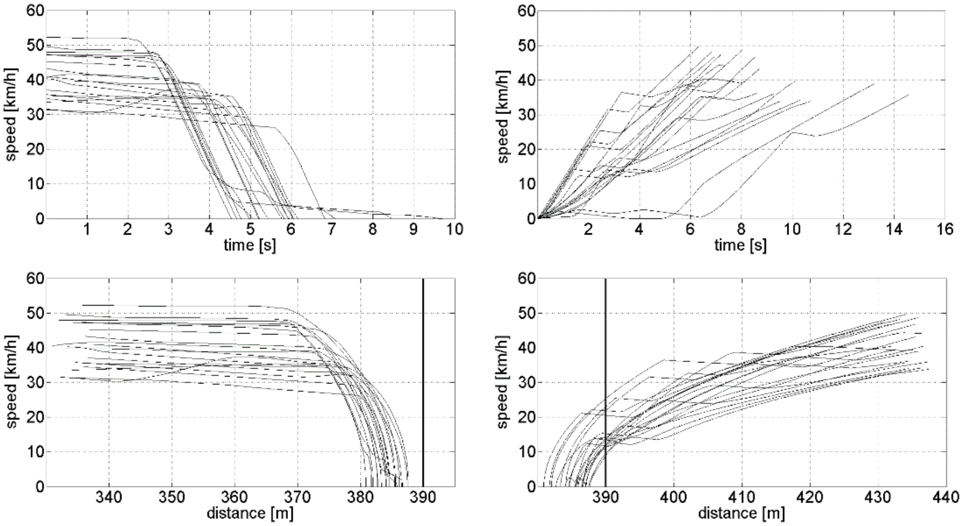


Figure 24 Individual speed visualized by means of a time (upper graphs) and distance (lower graphs) approach for the 50 m zone before stopping (left graphs) and 50 m zones after stopping (right graphs). The vertical black line indicates the stop line. (dataset 2)

The different ANOVAs and pairwise comparisons for **dataset 3** show significant differences in mean speed between the three approaches in the last subzone before the intersection. During this last subzone, drivers were decelerating while approaching the intersection. The time sampling approach underestimates mean speed between 9% and 15%, compared to the interpolated data and formula 8.

Based on Figure 25 we can conclude that drivers' deceleration maneuver was strongest during the last 200 m before the intersection (zone 21-24).

The difference between the three approaches was minimal in the 50 m zones between 200 and 50 m before the intersection (i.e., zone 21, 22 and 23). Nevertheless, the time sampled mean speeds in the last 100 m and 200 m zone before the intersection showed an underestimation of the driving speed between 10% and 15% compared to the interpolated data and formula 8. This increasing underestimation (9% during last 50 m zone, 10% during last 100 m zone and 15% during last 200 m zone) can be related to the high number of sampled data points in this last road stretch while approaching the intersection at a lower speed, compared to the lower number of sampled data points during the first part of the motorway exit. As an example, during the last 200 m of the motorway exit (i.e., 17% of the 1200 m long motorway exit), 25% of all data points are sampled. In comparison, during the first 200 m of the motorway exit, 11,70% of all data points are sampled. This finding is the logical consequence of the negative correlation between speed and number of sampled data points (see paragraph 2.4.2 A and Figure 19). When the last zone before the intersection lengthens (i.e., 400, 600 or 1200 m), the relative difference between the three approaches diminishes again (13% during last 400 m, 10% during last 600 m and 9% during last 1200 m). This decreasing effect can be attributed to the influence of the large number of sampled low speed data during the last 200 m that are averaged in the larger subzones.

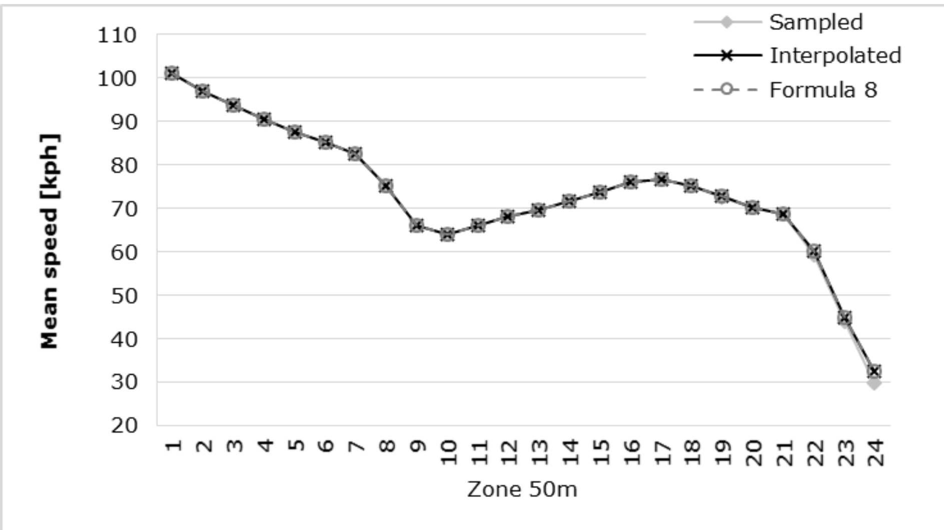


Figure 25 Mean speed at motorway exit (dataset 3)

The hazard situations in **dataset 4 and 5** show comparable results to the intersection approaches. In these situations, drivers perform a strong decelerating maneuver on a relatively short road stretch resulting in a significant underestimation of mean speed based on sampled data compared to interpolated data or formula 8. During the approach to the hazard location, the relative difference ranged from 17% to 25% in dataset 4 and 97% in dataset 5. In addition, the mean speed during the first 50 m after passing the hazard location in dataset 5 was also underestimated by 3%.

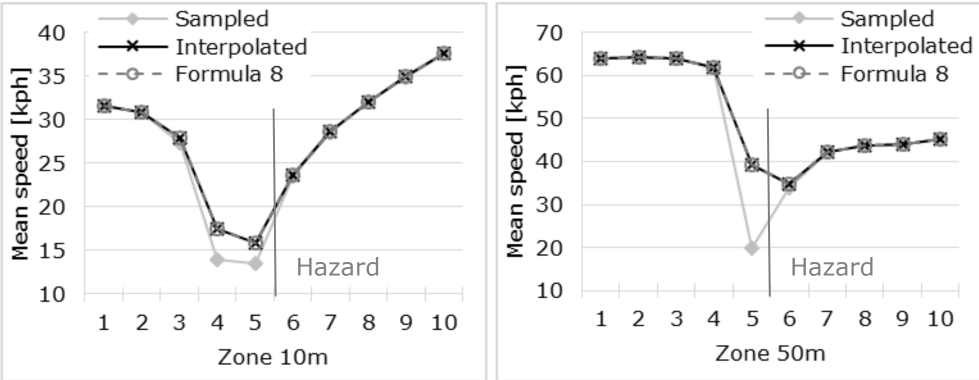


Figure 26 Mean speed in (a) 10 m zones near hazard (dataset 4) and (b) 50 m zones near hazard (dataset 5)

C. Zonal-based analysis for mean lateral position based on dataset 1 and 4

The same ANOVAs for mean lateral position (LP) were performed for dataset 1, 2, 4 and 5. Only the ANOVAs for **dataset 1 and 4** showed a significant effect for *Approach* (dataset 1: $F_{(1,38)} = 13.9$, $p < .0005$; dataset 4: $F_{(2,86)} = 12.2$, $p < .0005$) and *Approach* × *Zone* (dataset 1: $F_{(1,46)} = 5.2$, $p = 0.016$; dataset 4: $F_{(2,96)} = 16.6$, $p < .0005$). However, compared to mean speed where we found large differences between the sampled data on the one hand and interpolated data and formula 8 on the other hand, the pairwise comparisons revealed rather negligible differences of less than 1% for dataset 1 and 2% for dataset 4 (between 20 and 10 m before the hazard: mean LP based on sampled data: 1.289 m, interpolated data: 1.311 m and formula 7: 1.311 m).

The results for **dataset 2 and 5** showed no significant main effect for the factor *Approach*, neither for the interaction effect. These result indicates that there were no significant differences between the different approaches to calculate mean LP.

2.4.5 Discussion and practical recommendations

By means of five datasets, one related to a curve section (dataset 1), two focused on stopping and accelerating behavior nearby an intersection (dataset 2 and 3) and two additional ones focusing on a hazard situation (dataset 4 and 5), the difference between (1) point location based analysis and (2) zonal-based analysis using different approaches was illustrated.

The **point location based analysis** for the curve section compared the nearest point speed value with the interpolated speed value at seven point locations nearby and along the curve. The results showed that the nearest value approach provided a very good approximation of interpolated values. Based on this, we can conclude that it is not necessary to calculate the interpolated value for point location based analysis. However, we would like to emphasize that the nearest value might slightly over- or underestimate the actual parameter value, particularly on road segments with high driving speeds (such as on a motorway) because the distance between the specific point of interest and the nearest point might be relatively large, especially in case of small time sampling frequency rates.

For the **zonal-based analysis**, mean speed was analyzed for five datasets that were collected by means of time sampling and was based on:

A. All sampled raw data in the time interval that corresponds with the distance interval of interest;
B. The interpolated values in a zone using formula 6;
C. The coefficient of variation using formula 8.

The results for all datasets (except dataset 1) showed that the mean speed based on raw sampled data might underestimate mean speed values compared to approach B and C. The underestimations were especially present in the approaching zones just before the intersection or the hazard location because of the large speed variations due to stopping and accelerating. In order to avoid these underestimations, we advise to use the piecewise linear interpolation technique using formula 6 (approach B) or the presented integral formula 8 (approach C) to calculate the mean speed value in a zone as both approaches provide similar results.

The same approaches were used for mean LP in four datasets. Only for approach C, formula 7 was used instead of formula 8 because the latter is only applicable to mean speed. Due to the negative correlation between drivers' speed and the number of sample data points for time sampling (see Figure 19) speed values are always lower in subzones where driving speed is lower and thus result in an underestimation of mean speed based on sampled data compared to the other two approaches. The calculation of other driving parameter means, such as lateral position, based on raw sampled data might over- or underestimate the mean driving parameter value compared to the mean value based on the interpolation technique or the presented formula 7. Unlike mean speed, it is not possible to predict whether the different approaches over- or underestimate each other because the driving parameter can both decrease or increase in the subzone where driving speed is lower, and thus weigh more in the mean value based on sampled data. The analysis of the datasets in this paper show only negligible differences in mean LP between the three approaches. However, we can assume that larger differences can be expected in datasets where large swerving behavior is observed in combination with substantial speed variations. In order to be consistent, we recommend to always apply the interpolation technique for other driving parameters like mean LP.

In sum, the interpolation technique (formula 6) and the integral formulas (formula 7 and 8) are preferred over the use of raw sampled data to calculate mean parameter values. In addition to averages, the **dispersion (standard deviation) of a driving parameter** might be interesting. The simple integral formula is however not applicable for the calculation of SD values. Therefore, the interpolation procedure provides a good approximation of the SD value. Because the SD of a parameter value is related to the mean parameter value, it is impossible to predict whether the SD based on raw sampled data might be an under- or overestimation compared to the SD value based on interpolated data. The differences between both approaches might be the subject of future research. In addition, it might be interesting to compare the different approaches for other driving parameters, in other driving circumstances, with longer zones of interest (for instance several kilometers) or in other driving simulators.

An important issue relates to the used **step size** when running piecewise interpolation on a set of equidistant points. A good rule of thumb is to choose the step so that the number of created interpolation points in a certain zone is in line with the number of sampled data points. In dataset 1, 3 and 5 we used a step size of 1 m, whereas 0.5 m was used for dataset 2 and 4. This smaller step size was used because the size of the analysis zones was smaller and cars stopped very quickly and then left again from standstill near the intersection and the hazard location. This driving behavior has a significant impact on the number of sampled parameter values. Considering a motorway study, the step size can be increased to a value between 2 and 5 meters. The step sizes used in this paper are rather small and thus provide more detail compared to studies from Montella and colleagues (2013; 2015a) who used a 20 Hz sampling frequency and a step size of 5 m. In case of a point location based analysis, the choice of the interpolation step is redundant because one is only interested in the nearest parameter values.

Finally, besides the improved calculation for mean parameter values based on the interpolation technique and the integral formulas, these approaches also provide the opportunity to **visualize** the driving parameters for individual subjects in a distance comparable way. This advantage is also illustrated in Figure 21 and Figure 24.

2.4.6 Conclusions

This paper investigates the effect of different approaches to calculate parameter values based on driving simulator data. This data processing takes place before the statistical analysis. For point location based analysis, the nearest value showed to be a very good approximation of the interpolation value. Based on this, we can conclude that it is not necessary to calculate the interpolated value for point location based analysis.

For zonal-based analysis, significant differences were discovered between mean parameter values based on raw sampled data, on the one hand and mean parameter values based on interpolated data and the integral formulas on the other hand. The typical differences ranged from 9% to 25%. Mean speed values were significantly underestimated by the raw sampled data in some zones as the result of large speed variations within the zone of interest. For other driving parameters such as lateral position, the mean value based on raw sampled data might over- or underestimate the mean driving parameter value compared to the mean value, based on the interpolation technique or the presented integral formula (7). Nevertheless, the established differences in mean LP in this paper were negligible.

In sum, the interpolation technique and the integral formulas are preferred over the use of raw sampled data to calculate mean parameter values. Based on this paper, we would like to demonstrate that it is very important to mention the data processing approach in the driving simulator methodology. Finally, it is important to investigate driving simulator data starting from a descriptive point of view by means of a graph.

Chapter 3

EMPIRICAL STUDIES CONCERNING RURAL-TO-URBAN TRANSITIONS

3.1 A SIMULATOR STUDY ON THE IMPACT OF TRAFFIC CALMING MEASURES IN URBAN AREAS ON DRIVING BEHAVIOR AND WORKLOAD

This chapter is based on:

Ariën, C.; Jongen, E.M.M.; Brijs, K.; Brijs, T.; Daniels, S.; Wets, G. (2013) A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload. In *Accident Analysis and Prevention, 61,* 43-53. doi: 10.1016/j.aap.2012.12.044. [web of science: 5 year impact factor 2.699].

Proceedings:

Ariën, C.; Jongen, E.M.M.; Brijs, K.; Brijs, T.; Wets, G. (2011) A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload. In: Proceedings of 3rd International Conference on Road Safety and Simulation, Indianapolis (USA), September 14-16, 2011.

Abstract

This study examined the impact of traffic calming measures (TCM) on major roads in rural and urban areas. More specifically we investigated the effect of gate constructions located at the entrance of the urban area and horizontal curves within the urban area on driving behavior and workload. Forty-six participants completed a 34 km test-drive on a driving simulator with eight thoroughfare configurations, i.e., 2 (curves: present, absent) x 2 (gates: present, absent) x 2 (peripheral detection task (PDT): present, absent) in a within-subject design.

PDT performance (mean response time (RT) and hit rate) indicated that drivers experienced the road outside the urban area as cognitively less demanding relative to the more complex road environment inside the urban area. Whereas curves induced a speed reduction that was sustained throughout the entire urban area, variability of acceleration/deceleration and lateral position were increased. In addition, PDT performance indicated higher workload when curves were present (versus absent). Gate constructions locally reduced speed (i.e., shortly before and after the entrance) and slightly increased variability of acceleration/deceleration and lateral position nearby the entrance. However, the effects on standard deviation of acceleration/deceleration (SDAD) and standard deviation of lateral position (SDLP) are too small to expect road safety problems.

It can be concluded that both curves and gate constructions can improve road safety. Notwithstanding, the decision to implement these measures will depend on contextual factors such as whether the road serves a traffic-, rather than a residential function.

Highlights

- Road outside urban area is cognitively less demanding than inside the urban area
- Curves decrease mean speed but increase SD acceleration/deceleration and SDLP
- PDT performance indicated higher workload when curves were present
- Gates locally reduced speed but increased SD of acceleration/ deceleration and SDLP
- Curves and gate constructions can improve road safety

3.1.1 Introduction

Experimental research indicates that, in terms of road safety, the transition between rural and urban areas is a serious problem (Charlton & O'Brien, 2002; Galante et al., 2010; M. Taylor & Wheeler, 2000). From the perspective of road safety engineering, a speed reduction is often implemented within the transition zone to urban areas serving not only a residential function, but also a traffic function (i.e., allowing the traffic to drive through). But in many situations speed limits on rural roads are higher than in urban areas, and drivers have experienced a sustained period of driving at higher speed before accessing an urban area. This might have detrimental effects leading to reduced cognitive arousal and workload (i.e., *mental underload*), and the risk of underestimating the actual travel speed, (i.e., a phenomenon referred to as *speed adaptation*). As explained further below, mental underload and speed adaptation can cause unsafe situations, mainly because of the inadequate way in which speed reduction is performed (Dewar & Olson, 2007; Hallmark et al., 2007; NRA National Roads Authority, 2005; Safetynet, 2009b). Appropriately designed transition zones are therefore of crucial importance for road safety.

3.1.2 Objectives

The present study aims to examine the influence of traffic calming measures (TCM) on road safety by means of a driving simulator. Several studies established that the combination of gate constructions nearby the entrance of the urban area with additional traffic calming measures further along the through route are most effective (Harkey & Zegeer, 2004; Taylor and Wheeler, 2000; Village Speed Control Working Group, 1994; European Transport Safety Council, 1995). Therefore, we are also interested in the influence of gate constructions in the transition zone between outside and inside the urban area in combination with horizontal curves within the urban area on driving performance and workload. The following section contains an overview of the published findings related to these factors.

3.1.3 Theoretical background

A. Self-explaining roads and traffic calming measures

The transition while entering an urban area is a well known problem within the literature on self-explaining roads (SER) (Charman et al., 2010; Martens et al., 1997). Typically rural environments are less complex than urban areas and several studies have shown that lower complexity goes together with less cognitive demand (e.g. Edquist et al., 2012; Patten et al., 2006; Engström et al., 2005; Horberry et al., 2006; Cantin et al., 2009; Stinchcombe and Gagnon, 2010; Greibe, 2003). Such a reduction in demand in combination with an increased risk for underestimating the actual travel speed, might create dangerous situations. Appropriately designed transition zones are therefore of crucial importance for road safety.

To address the problematic transition when entering urban areas, the European Transport Safety Council (ETSC European Transport Safety Council, 1995) proposed specific principles for the design of transition zones that lie in between the approach to and the entrance of urban areas on major routes. One such principle is that measures taken in the transition or threshold zone from a rural road to urban areas should be complemented by measures further along the route inside the urban area (i.e., the so-called *through route*). As for the design of the transition zone, an important principle is that different individual TCMs "*should be such that they achieve a cumulative effect culminating at a feature called the gateway to the town or village*" (ETSC European Transport Safety Council, 1995) . Typically, within a wide range of possible measures to be taken, gate constructions are implemented in the transition zone, whereas curves are used along the through route inside the urban area (Charman et al., 2010; Hallmark et al., 2007; ETSC European Transport Safety Council, 1995; ITE Institute of Transportation Engineers & FHWA Federal Highway Administration, 1999; M. Taylor & Wheeler, 2000; Ogden, 1996).

Both field and simulator experiments have been executed to examine the effect of a variety of TCMs on major cross-town roads. In general, the context and type of measure have a large influence on the established results (Dixon et al., 2008; Hallmark et al., 2007). The Village Speed Control Work Group (1994) analyzed 24 village traffic calming schemes and obtained mean speed reductions between 2 and 16 kph for the gateway schemes. As a result, all injury accidents and fatal/serious injury accidents decreased by about 25% and 50%, respectively (Department for Transport, 2000). The Federal Highway Administration (Federal Highway Administration, 2009b) reported speed reductions up to 24 kph in France, Denmark and the UK. However, speed reductions of 8 to 10 kph were more typical (Department for Transport, 1993). Driving simulator studies (Dixon et al., 2008; Federal Highway Administration, 2010; Galante et al., 2010) showed speed reductions from 6.4 to 17 kph in the transition zone. However, the results of Dixon et al. (2008) and Galante et al. (2010) indicate that these speed reductions do not consistently extend beyond the vicinity (300 to 400 m) of the TCM. In general, gate constructions complemented by measures in the through route are most effective (County Surveyor's Society, 1994; M. Taylor & Wheeler, 2000). Therefore, we are also interested in the combination of gates nearby the entrance of the urban area with curves situated further along the through route.

B. Driving performance and road safety

The present study hinges upon the idea that drivers' behavior should be approached as a multi-dimensional, rather than a single-dimensional concept, i.e., as the combination of both longitudinal and lateral driving parameters (Rosey et al., 2008).

The longitudinal dimension mostly applies to the way in which drivers manage their speed. Among the different speed-related parameters known in the literature, mean speed is very often used as measure for safe driving, mainly because elevated crash risk and severity have been related to an increase in mean speed (Safetynet, 2009b; European Commission, 1999; Shinar, 2007). Besides mean speed, standard deviation of longitudinal acceleration and deceleration (SDAD) is a popular parameter since it indicates the degree to which drivers are able to keep *variations* in speed under control. When drivers abruptly change their speed, the homogeneity of the traffic flow is disrupted and the time to anticipate and/or react decreases. This might result in an increased risk for rear-end collisions (Marchesini & Weijermars, 2010).

The lateral dimension of driving behavior relates more to managing the vehicle's horizontal position within the driving lane. Lack of a harmonized lane position is one of the primary factors in single-vehicle run-off the road and head-on collisions (Rosey et al., 2008). In the literature the variation or standard deviation of lateral position (SDLP) is very often used as an indicator for lateral trajectory control. In addition, SDLP is a sensitive measure of driver impairment for example due to increased mental workload and various drugs (De Waard, 1996; Ramaekers, 2003).

By investigating both the longitudinal and lateral dimensions of driving behavior, this study will come to a multidimensional evaluation of different thoroughfare configurations.

C. Workload and driving performance

Specialists in human factors and road safety agree on the idea that driving performance is closely related to the attentive state of the driver (Wickens & Hollands, 2000). The degree of arousal influences both the amount and allocation of attentional resources available (Proctor & van Landt, 1993). The Yerkes-Dodson law describes the relation between driving performance and arousal as an inverted U-function with poor performance at both low and high levels of arousal and optimal performance at medium levels of arousal (Fitzpatrick et al., 2010; Fuller, 2005; Fuller & Santos, 2007; Weller et al., 2006).

Measurement of mental or cognitive workload has been the primary method for determining levels of arousal. According to Brookhuis and de Waard (2001) mental workload is the proportion of mental capacity that is required for the performance of a task (such as driving), with task complexity being determined by the interaction between the capability of the driver and the (cognitive) demands imposed by the task. Fuller's task-capacity interface model describes that interaction more in detail. The model argues that drivers, via behavioral adaptations, seek for task difficulty- or workload homeostasis so that an optimal performance level can be reached (Fuller, 2005). When workload is too low (i.e., underload) errors may arise from a loss of vigilance and boredom (Proctor & van Landt, 1993; Brookhuis & de Waard, 2001). Deficient performance has often been observed in monotonous tasks such as prolonged driving on a highway and is better known as '*highway hypnosis*' or 'driving without attention mode' (Campagne, Pebayle, & Muzet, 2005; Cerezuela et al., 2004; Rogé et al., 2004; Thiffault & Bergeron, 2003). This phenomenon is defined as a mental state showing sleepiness symptoms and attention slips resulting from driving a motor vehicle for a sustained period in a highly predictable environment with low event occurrence. This is the case for instance with motorways and very familiar roads (Chan & Atchley, 2009). High task demand, on the other hand, can result in so-called *overload* with mental workload imposed on the driver being too high. In cases alike, behavioral adaptation in the form of increased effort investment, implementation of more (or less) demanding working strategies and skipping subsidiary tasks, is needed to keep workload as close to the optimum as possible (Wickens & Hollands, 2000).

As for the present study, European urban areas typically are preceded by a rather monotonous road environment, thereby increasing the risk of minimal vigilance and a state of mental underload when approaching the urban areas. To prevent the potential occurrence of driving errors when entering a more complex urban area, mental workload should increase so that driving performance remains optimal.

Interestingly, within the SER concept, both gate constructions and curves have been found to complicate road geometry, thereby making the driving task more difficult and thus, increasing the workload experienced, yet, without exceeding the boundaries of the optimal workload level (Charman et al., 2010; Charlton & O'Brien, 2002). Since the impact of gate constructions on workload appears to be local (Charlton & O'Brien, 2002; Dixon et al., 2008; Galante et al., 2010), curviness as an additional traffic calming measure might be needed in order to maintain the minimal level of workload required to drive safely throughout the rest of the thoroughfare.

In addition to driving behavior, workload will be investigated in the present study. Several methods have been developed to give an indication of drivers' workload level such as primary and secondary task performance, psycho-physiological measures and self-report measures (Verwey & Veltman, 1996; Godley, 1999). In this study the Peripheral Detection Task (PDT) will be used as secondary task, requiring the detection of a red square, presented in the upper-left visual field

(Jahn, Oehme, Krems, & Gelau, 2005; Martens & van Winsum, 2000; Patten, Kircher, Östlund, Nilsson, & Svenson, 2006). Several driving (simulator) studies have shown that mean response time (RT) and mean hit rate, as performance measures for PDT, are sensitive to changes in demands of the driving task with lower mean RT and higher mean hit rates related to lower driving task demands and workload (P. C. Burns, Knabe, & Tevell, 2000; D. Crundall & Underwood, 1998; L. Harms & Patten, 2003; Nakayama, Futami, Nakamura, & Boer, 1999; Olsson & Burns, 2000; in Jahn et al., 2005; Martens & van Winsum, 2000; Patten et al., 2006; Patten, Kircher, Östlund, & Nilsson, 2004). PDT will be used here to verify whether drivers experience the major road outside the urban area as monotonous, and thus less task demanding, compared to the more complex through route.

3.1.4 Research questions

Based on the information above, in the present study the following three research questions will be addressed:

1. Do drivers experience the road segment outside the urban area as monotonous relative to the more complex road environment inside the urban area?
2. Do gate constructions influence driving behavior near the entrance of a thoroughfare? If so, how far in distance along the road does the influence reach before and after the gate construction?
3. Do horizontal curves influence driving behavior and workload?

As will be further outlined, in the driving simulator, following a 2 (curves: present, absent) by 2 (gate constructions: present, absent) by 2 (peripheral detection task (PDT): present, absent) within-subject design, four different thoroughfare configurations will be presented twice: once with and once without secondary PDT.

Four different analyses will be executed. Firstly, a comparison will be made of performance on the PDT as a measure for workload outside versus inside the urban area in function of gate constructions and curves (cf. research question 1). Secondly, three driving performance measures will be verified over various distances before and after the entrance of the urban area in function of gate constructions, curves and PDT (cf. research question 2). Finally, the last research question is expounded by two analyses. First, three driving performance measures will be verified for the analysis zone before the middle of the thoroughfare and after the middle of the thoroughfare in function of gate constructions, curves and PDT. Second, performance on PDT will be verified for the same analysis zones in function of gate constructions and curves.

3.1.5 Methodology

A. Participants

Fifty-five volunteers participated in the study. All gave informed consent. Nine participants were excluded. Three did not finish the experiment due to simulator sickness and six were identified as outliers (two drove at exaggerated mean speed and four had a SDAD more than three SD from the group's mean). Thus, 46 participants (24 men), equally divided over five age categories from 20 to 60 years and older (mean age 45.3) remained in the sample. All had (corrected to) normal vision. Age and gender were not taken into account as between-subject factors in the statistical analyses.

B. Driving simulator

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-base (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual and auditory feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images. Three projectors offer a resolution of 1024 × 768 pixels and a 60 Hz refresh rate. The sounds of traffic in the environment and of the participant's car were presented. Data were collected at frame rate.

C. Scenario

Design

Following the earlier mentioned 2×2×2 within-subject design, four different thoroughfare configurations were presented twice: once with and once without secondary PDT. Figure 27 and Figure 28 give an overview plan and a simulator view of the driving scenario.

Each thoroughfare had a length of 1270 m and was provided with signs indicating a speed limit of 50 kph throughout the whole urban area. In each thoroughfare, four intersections with right of way and accommodated by two zebra crossings were present. The ribbon development (Albrechts, 1999), present 200 m before and after the thoroughfare, merged into a stretch of continuous buildings inside the urban area. Four horizontal curves with a length of 100 m were part of the through road inside the curved thoroughfares: a first and last right curve (30°) and two middle left curves (40°). Gate constructions with non-parallel axis displacement and central reservation were located just after and before the border signs of the urban area in thoroughfares with gates. The geometric design of the gate construction is based on CROW (2004, p. 812) and is illustrated in Figure 27c. According to CROW (2004) this type of gate construction is the best alternative besides a roundabout and a parallel axis displacement.

A straight road segment of 2930 m between two thoroughfares was aimed at decreasing workload level and inducing speed adaptation. The first 990 m functioned as filler piece and were not analyzed; a total of 1940 m outside the urban area was thus reserved for analyses. The monotonous road environment contained a wide view with open fields and was occasionally alternated with a stretch of forest. A curve of 20° with a curve length of 100 m was located 300 m before and after the thoroughfare and a speed limit of 70 kph was indicated by a 70 kph sign and drivers were free to decide whether to comply or not.

The road was divided in two lanes of 3.25 m width with one lane for each travel direction. The cycle lanes were separated from the traffic lanes by a green strip outside the urban area and by a parking lane inside the urban area. Traffic volume on the opposite lane was based on existing traffic counts in thoroughfares (Van Hout & Brijs, 2008). There was neither traffic present in the direct vicinity of the gate constructions nor directly in front of or following the driver. Weather conditions were sunny and dry.

Secondary Peripheral Detection Task (PDT)

The PDT involved detection of a red square, presented in the upper-left visual field as quickly as possible (Jahn et al., 2005; Martens & van Winsum, 2000; Patten et al., 2006). The red square appeared at 6 possible locations in an area of 11°-23° to the left of the center of the steering wheel and 2°- 4° above the horizon. To ensure that the red square was always visible, it was presented on a black bar that was projected and kept on screen during the scenarios where the PDT was presented.

The signal rate was adjusted so that the interval between two presentations was 4-6 seconds. The red square was visible for a maximum of 2s. Within these 2s, it disappeared as soon as the driver pressed the horn with the left thumb. Drivers were instructed to place the left thumb on the horn with the other fingers on the steering wheel during the whole drive – thus also when PDT was absent – to minimize variation between driving with and without PDT.

In total 42 stimuli were presented, distributed evenly across the six locations: 24 stimuli were presented outside the urban area, of which 15 (stimuli 7-20) were used in the analyses, and 18 stimuli (stimuli 25-42) were presented and analyzed inside the urban area.

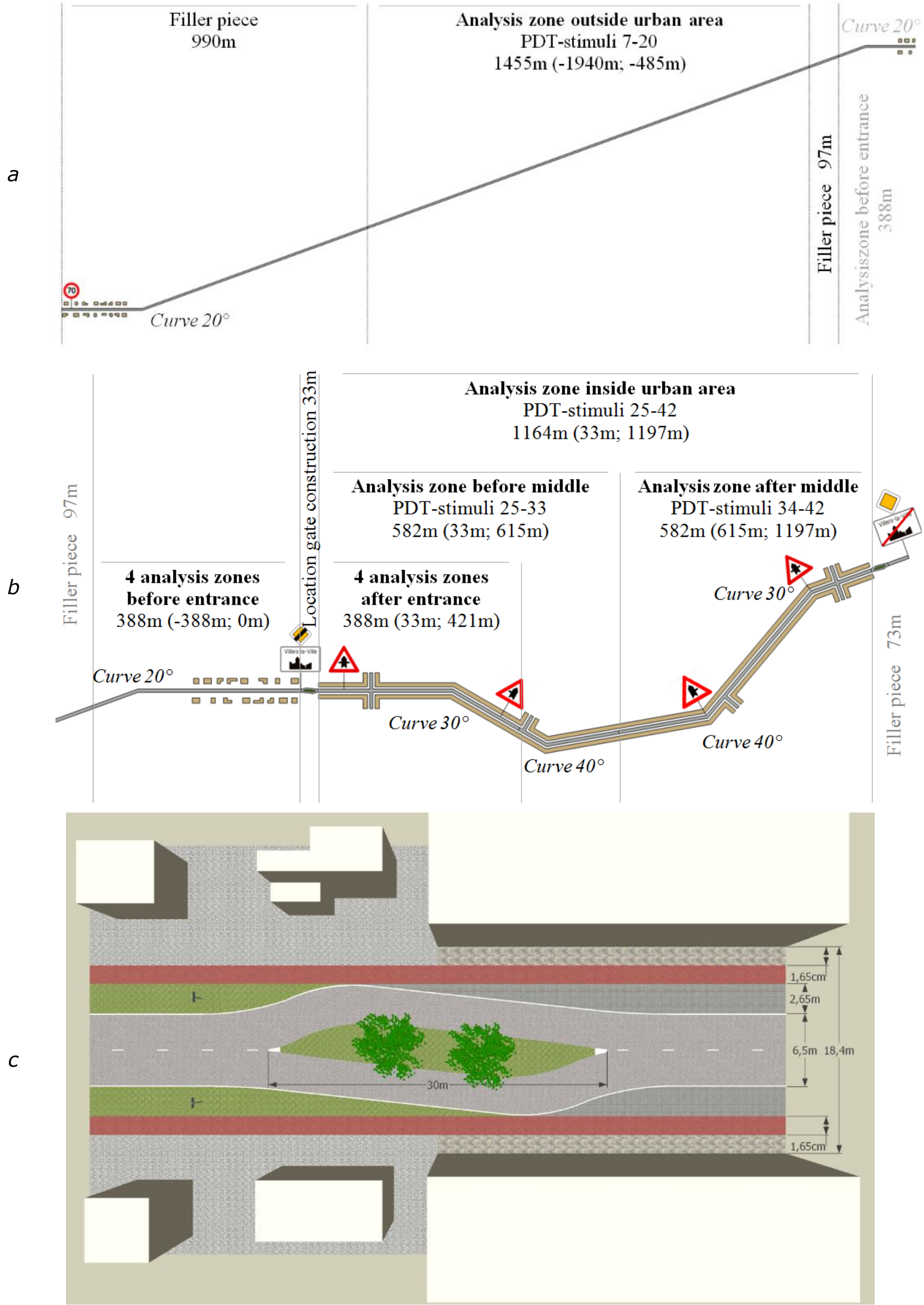
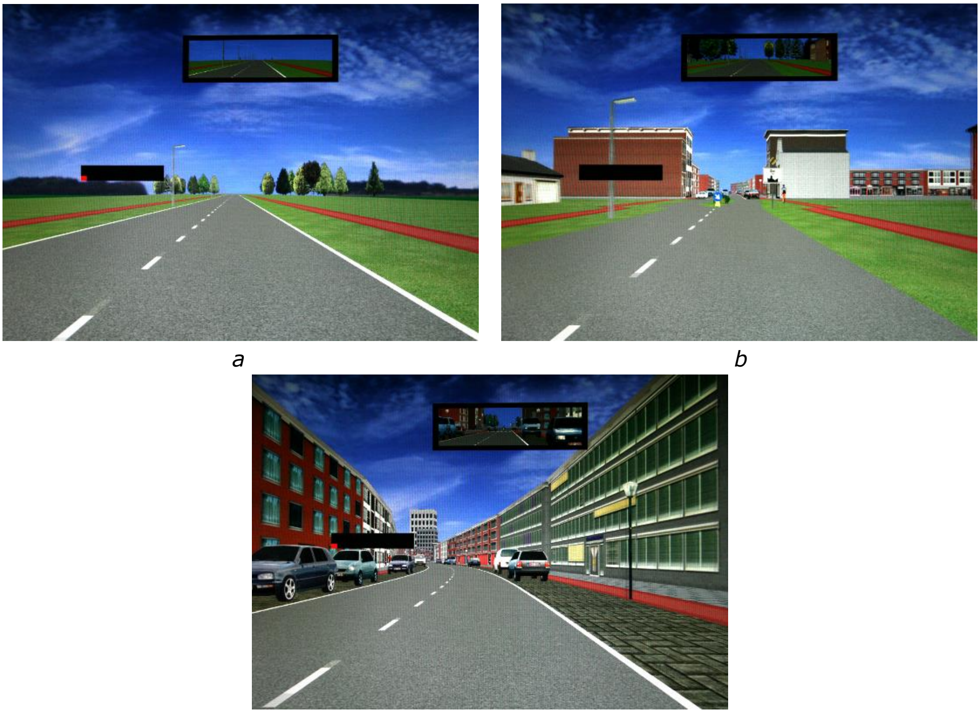


Figure 27 Plan view of (a) straight road followed by (b) curved thoroughfare featured by (c) gate constructions



a b

c

Figure 28 Simulator view with PDT-stimuli of (a) straight road, (b) transition with gate construction between outside and inside urban area, (c) inside curve thoroughfare

Procedure

The main session consisted of a practice session and an experimental session. The *practice session* consisted of two phases. First, a thoroughfare (2.4 km, 3 minutes) with only curves was presented to acquaint the drivers with the experience of driving in a simulator. During the second practice phase, the PDT was explained and presented. The trip consisted of two thoroughfare configurations (4.4 km, 5 minutes), a straight and a curved one, both with gate constructions similar to those in the experimental session.

The *experimental session* consisted of one trip (34 km, 35 minutes) in which the four different thoroughfare configurations were presented twice: once with and once without PDT. Each of the four different thoroughfares was presented once before it was repeated. Blocks of two thoroughfare configurations without PDT were alternated with blocks of two thoroughfares with PDT. Order of the four different thoroughfare configurations was counterbalanced via a Latin square design with an opposite order of the last two blocks in comparison with the first two blocks. Half of the participants started without PDT and the other half started with PDT. Thus in total, there were eight different orders, balanced between subjects.

At the start of the experiment participants were asked to give their informed consent and to fill out a form with their personal data (e.g. gender, date of birth). Drivers were instructed to drive as they normally do, to place their left hand on the horn during the whole drive and to prioritize the driving task above secondary PDT. Between the two sessions, these instructions were repeated.

Data collection and analysis

Driving performance measures for longitudinal and lateral control were recorded. Longitudinal control was measured by means of mean driving speed [kph] and standard deviation of longitudinal acceleration/deceleration (SDAD) [m/s²]. Lateral control was measured by standard deviation of lateral position (SDLP) [m]. The workload level was measured by the performance on PDT. Mean response time (RT) and mean hit rate were collected for all stimuli.

Before analyzing the data, outliers were determined. For *PDT* incorrect trials, misses and trials with RT faster than 150 ms and slower than 2000 ms were excluded. Participants with less than 10 correct trials in 15 trials outside the urban area and less than 12 correct trials in 18 trials inside the urban area were labeled as outliers. One female person was excluded from the sample. The detection of outliers in the *driving performance* data was done on the basis of 32 box plots for each parameter (2 Curves x 2 Gates x 2 PDT x 2 Analysis zone (outside-inside urban area / before-after middle). Participants with 25% (8/32) of their parameter values exceeding three times the inter quartile distance were labeled as outliers (Denker et al., 1998, p. 69). Three participants were outliers on SDAD. Thus, 46 participants remained in the sample.

Four main analyses were executed on these parameters. Prior to each of these analyses two multivariate analyses of variance (MANOVA's) were conducted to provide an overall measure of driving performance and workload as a function of the experimental conditions. Univariate statistical analyses were then carried out by entering the different measures of driving performance (mean speed, SDAD and SDLP) as dependent measures into three separate repeated measures ANOVAs with within-subject factors Curves (2: absent, present), Gates (2: absent, present), PDT (2: absent, present) and Analysis zone (2: before / after middle of thoroughfare or 8: zones before / after entrance of urban area). In addition, univariate statistical analyses were conducted by entering the different measures of workload (mean RT and mean hit rate) as dependent measures into two separate repeated measures ANOVAs with within-subject factors Curves (2: absent, present), Gates (2: absent, present) and Analysis zone (2: outside / inside urban area or 2: before / after middle thoroughfare).

To define the within-factor Analysis zone in the different analyses, the experimental section was first divided into 32 successive 97 m zones, of which 20 were outside the urban area (-1940 m; -485 m) and 12 inside the urban area (33 m; 1197 m). The beginning of the 33 meters long gate construction is thus used as zero point. Negative values refer to analysis zones situated before the entrance and positive values refer to analysis zones situated after the gate construction. The road segment of the gate construction was excluded from the analysis. For the different analyses, different "Analysis zones" were taken by averaging across specific successive 97 m zones, as defined below. Figure 27 gives an overview of the different analyses.

For all analyses, P-value was set at 0.05. For MANOVA's F- and probability values are reported. ANOVA's were corrected for deviations from sphericity (Greenhouse-Geisser epsilon correction) and the corrected F- and probability values are reported.

The first analysis was a *road environment workload manipulation check*, verifying whether drivers indeed experienced the road segment outside the urban area as monotonous as reflected by lower workload relative to the more complex thoroughfare. Mean PDT RT and hit rate for the monotonous section (-1940 m; -485 m or stimuli 7-20) outside the urban area were compared with the road segment inside the urban area (33 m; 1197 m or stimuli 25-42). A 2 (Curves) x 2 (Gates) x 2 (Analysis zone: outside / inside urban area) MANOVA was conducted for mean PDT RT and hit rate.

The second analysis was carried out to determine the influence of gate constructions on driving performance measures near the *entrance* of a thoroughfare. Four 97 m-zones before the entrance (-388 to -291 m; -291 to -194 m; -194 to -97 m; -97 to 0 m) and four 97 m-zones after the entrance (33 to 130 m; 130 to 227 m; 227 to 324 m; 324 to 421 m) were of interest. A 2 (Curves) x 2 (Gates) x 2 (PDT) x 8 (Analysis zone: 4 zones before entrance and 4 zones after entrance) MANOVA was carried out for the dependent variables mean speed, SDAD and SD LP. The factor PDT was of no interest and thus not reported. PDT workload measures (i.e., mean RT and hit rate) were not taken into account because the limited amount of presented stimuli would not produce reliable results.

The third and fourth analyses were carried out to evaluate driving performance and PDT workload measures *throughout the thoroughfare*. Both the road segments before the middle (33 m; 615 m or stimuli 25-33) and after the middle (615 m; 1197 m or stimuli 34-42) of the thoroughfare were of interest. A 2 (Curves) x 2 (Gates) x 2 (PDT) x 2 (analysis zone: before / after middle) MANOVA was conducted for the dependent variables mean speed, SDAD and SD LP. The factor PDT was of no interest and thus not reported. In the fourth analysis, PDT workload measures were examined using the same Analysis zones (before / after middle) in a 2 (Curves) x 2 (Gates) x 2 (Analysis zone) MANOVA for mean RT and mean hit rate.

3.1.6 Results

A. Road environment workload manipulation check

The MANOVA revealed a significant main effect for Analysis zone ($F_{(3,43)} = 50.0$, $p < .0005$). Subsidiary univariate analyses showed that mean RT was lower outside the urban area (M = 610.036, SD = 13.946) than inside the urban area (M = 687.382, SD = 14.161) ($F_{(1,45)} = 95.4$; $p < .0005$). The opposite was true for mean hit rate with lower mean hit rate inside the urban area (M = 97.192, SD = .417) than outside the urban area (M = 99.495, SD = .154) ($F_{(1,45)} = 29.2$, $p < .0005$).

To summarize, the assumption that the workload level decreased outside the urban area is supported as reflected by a higher RT and a lower hit rate inside than outside the urban area.

B. Influence of gate constructions on driving behavior near the entrance

The multivariate and univariate statistics for the analysis near the entrance are reported in Table 8. The MANOVA revealed a significant main effect of Curves, Gates and Analysis zone. However, there was also an interaction of *Curves × Analysis zone* and *Gates × Analysis zone*. Subsidiary univariate analyses for mean speed, SDAD and SDLP revealed a main effect for Curves, Gates and Analysis zone. However, there also was a (marginally significant) interaction of *Curves × Analysis zone* and an interaction of *Gates × Zone*. Post-hoc tests for both interactions are described below and illustrated for Gates × Analysis zone in Figure 29.

Mean speed

Separate tests for each level of Analysis zone showed that mean speed was lower when gates were present from 97 m before ($F_{(1,45)} = 26.4$, $p < .0005$) to 97 m after the gate ($F_{(1,45)} = 43.5$, $p < .0005$).

SDAD

Separate tests for each level of Analysis zone showed that SDAD was (marginally) lower when no gates were present between -194 and -97 m ($F_{(1,45)} = 3.1$, $p = .088$), between -97 and 0 m ($F_{(1,45)} = 13.7$, $p = .001$), between 33 and 130 m ($F_{(1,45)} = 18.4$, $p < .0005$), between 130 and 227 m ($F_{(1,45)} = 4.4$, $p = .042$) and between 227 and 324 m ($F_{(1,45)} = 5.2$, $p = .028$).

To summarize, from 194 m before the entrance till 282 m after the entrance SDAD was lower when no gates were present than when there were gates.

Table 8 Multivariate and univariate statistics for the analysis near the entrance

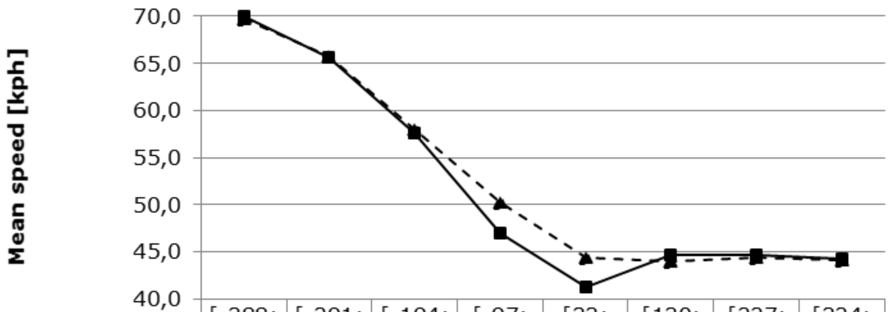
Variable	*F*	*p*
MANOVA *(dfs = 3, 43)*		
Curves	14.0	**< .0005**
Gates	38.4	**< .0005**
Analysis zone	128.5	**< .0005**
Curves × Gates	1.4	0.265
Curves × Analysis zone	6.1	**< .0005**
Gates × Analysis zone	11.7	**< .0005**
Curves × Gates × Analysis zone	1.0	0.539
Univariate statistics *(dfs = 1, 45)*		
Mean speed		
Curves	5.5	**0.024**
Gates	7.1	**0.010**
Analysis zone	562.7	**< .0005**
Curves × Analysis zone	2.1	*0.095*
Gates × Analysis zone	15.5	**< .0005**
SDAD		
Curves	1.7	0.201
Gates	39.2	**< .0005**
Analysis zone	16.5	**< .0005**
Curves × Analysis zone	< 1	0.654
Gates × Analysis zone	6.2	**0.001**
SDLP		
Curves	42.6	**< .0005**
Gates	78.3	**< .0005**
Analysis zone	35.4	**< .0005**
Curves × Analysis zone	35.2	**< .0005**
Gates × Analysis zone	41.2	**< .0005**

SDLP

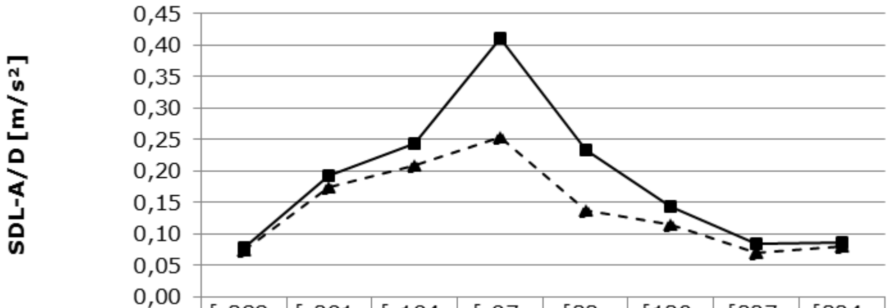
Separate tests for each level of Analysis showed that SDLP was (marginally) lower with than without gates between -388 and -291 m ($F_{(1,45)} = 4.1$, $p = .049$). SDLP was lower when no gates were present than when there were gates between -194 and -97 m ($F_{(1,45)} = 3.1$, $p = .085$), between -97 and 0 m ($F_{(1,45)} = 156.6$, $p < .0005$) and between 33 and 130 m ($F_{(1,45)} = 20.2$, $p < .0005$).

SDLP was lower when no curves were present than when there were curves between 130 and 227 m ($F_{(1,45)} = 10.4$, $p = .002$) (no curves: M = .072, SD = .004; curves: M = .085, SD = .004), between 227 and 324 m ($F_{(1,45)} = 150.9$, $p < .0005$) (no curves: M = .069, SD = .003; curves: M = .160, SD = .008) and between 3254 and 3351 m ($F_{(1,45)} = 42.5$, $p < .0005$) (no curves: M = .073, SD = .003; curves: M = .106, SD = .005).

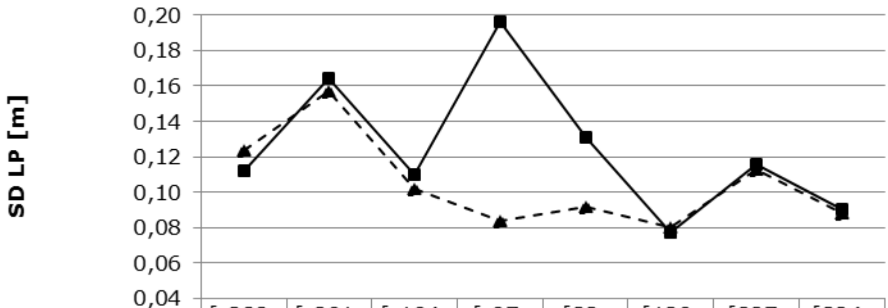
To summarize, SDLP was higher when curves were present in the near vicinity of the first curve and SDLP was higher when gates were present than when there were no gates from 97 m before the entrance till 97 m after the entrance.



	[-388; -291]	[-291; -194]	[-194; -97]	[-97; 0]	[33; 130]	[130; 227]	[227; 324]	[324; 421]
No gates	69,8	65,7	58,1	50,3	44,4	44,0	44,3	44,1
Gates	69,9	65,6	57,6	47,0	41,3	44,7	44,6	44,2



	[-388; -291]	[-291; -194]	[-194; -97]	[-97; 0]	[33; 130]	[130; 227]	[227; 324]	[324; 421]
No gates	0,074	0,175	0,208	0,253	0,138	0,114	0,069	0,08
Gates	0,077	0,192	0,244	0,412	0,234	0,143	0,085	0,087



	[-388; -291]	[-291; -194]	[-194; -97]	[-97; 0]	[33; 130]	[130; 227]	[227; 324]	[324; 421]
No gates	0,124	0,157	0,102	0,084	0,092	0,08	0,113	0,088
Gates	0,112	0,164	0,11	0,196	0,131	0,077	0,116	0,09

Figure 29 Mean speed, SDAD and SDLP for the interaction of Gates × Analysis zone

C. Influence of curves and gate constructions on driving behavior throughout the thoroughfare

The multivariate and univariate statistics for the analysis throughout the thoroughfare are reported in Table 9. The MANOVA revealed a significant main effect of Curves, Gates and Analysis zone. However, there was also an interaction of *Curves* × *Analysis zone*, *Gates* × *Analysis zone* and *Curves* × *Gates* × *Analysis zone*.

Table 9 Multivariate and univariate statistics for the analysis throughout the thoroughfare

Variable	*F*	*p*
MANOVA *(dfs = 3, 43)*		
Curves	44.2	**< .0005**
Gates	4.8	**0.006**
Analysis zone	65.6	**< .0005**
Curves × Gates	1.2	0.328
Curves × Analysis zone	11.1	**< .0005**
Gates × Analysis zone	11.9	**< .0005**
Curves × Gates × Analysis zone	3.5	**0.024**
Univariate statistics *(dfs = 1, 45)*		
Mean speed		
Curves	10.5	**0.002**
Gates	< 1	0.461
Analysis zone	105.0	**< .0005**
Curves × Analysis zone	2.5	0.122
Gates × Analysis zone	< 1	0.960
Curves × Gates × Analysis zone	1.5	0.222
SDAD		
Curves	14.0	**0.001**
Gates	12.9	**0.001**
Analysis zone	69.4	**< .0005**
Curves × Analysis zone	< 1	0.345
Gates × Analysis zone	28.8	**< .0005**
Curves × Gates × Analysis zone	3.8	*0.059*
SDLP		
Curves	132.0	**< .0005**
Gates	< 1	0.365
Analysis zone	23.4	**< .0005**
Curves × Analysis zone	24.0	**< .0005**
Gates × Analysis zone	5.0	**0.031**
Curves × Gates × Analysis zone	3.7	*0.062*

Mean speed

Subsidiary univariate analyses showed that mean speed was about 1 kph lower when curves were present ($F_{(1,45)} = 10.5$, $p = .002$) (no curves: M: 45.806, SD: .695; curves: M: 44.798, SD: .782) and lower before the middle ($F_{(1,45)} = 105.0$, $p < .0005$) (before middle: M: 44.244, SD: .750; after middle: M: 46.360, SD: .710).

SDAD

SDAD as a function of Gates × Analysis zone and SDLP as a function of Curves × Analysis zone and Gates × Analysis zone are summarized in Table 10.

Table 10 Means and SD of (a) SDAD for the interaction of Gates × Analysis zone and of SDLP for the interaction of (b) Curves × Analysis zone and (c) Gates × Analysis zone

	Before middle		After middle	
	M	SD	M	SD
SDAD as a function of Gates × Analysis zone				
No gates	0.091	0.007	0.067	0.006
Gates	0.120	0.008	0.066	0.006
SDLP as a function of Curves × Analysis zone				
No curves	0.077	0.003	0.078	0.003
Curves	0.124	0.004	0.149	0.007
SDLP as a function of Gates × Analysis zone				
No gates	0.098	0.003	0.115	0.004
Gates	0.104	0.003	0.112	0.004

Subsidiary univariate analyses for SDAD revealed a main effect for Curves (no curves: M: .079, SD: .006; curves: M: .093, SD: .006), Gates and Analysis zone. In addition to a significant two-way interaction of *Gates* × *Analysis zone* there was a marginally significant three-way interaction for *Curves* × *Gates* × *Analysis zone*.

Separate tests for each level of Gates showed that SDAD was lower after the middle than before (no gates: $F = 17.7$, $p < .0005$; gates: $F = 102.7$, $p < .0005$). Separate tests for each level of Analysis zone showed that before the middle SDAD was lower when no gates were present ($F = 23.0$, $p < .0005$; after the middle Gates: $F < 1$, $p = .748$).

To summarize, SDAD was lower when no gates were present, but this effect was only observed before the middle of the urban area. SDAD was lower without than with curves.

SDLP

Subsidiary univariate analyses for SDAD revealed a main effect for Curves (no curves: M: .078, SD: .003, curves: M: .137, SD: .005) and Analysis zone (before middle: M: .101, SD: .003, after middle: M: .113, SD: .004). However there were two significant two-way interactions for *Curves* × *Analysis zone* and *Gates* × *Analysis zone* and a marginal interaction of *Curves* × *Gates* × *Analysis zone*.

Separate tests for each level of Curves showed that when curves were present SDLP was lower before the middle ($F = 35.3$, $p < .0005$; no curves, Analysis zone: $F < 1$, $p = .767$). Separate tests for each level of Analysis zone showed that SDLP was lower when no curves were present (before the middle: $F = 148.7$, $p < .0005$; after the middle: $F = 101.4$, $p < .0005$).

Separate tests for each level of Gates showed that SDLP was lower before the middle (no gates: $F = 22.5$, $p < .0005$; gates: $F = 8.0$, $p = .007$). Separate tests for each level of Analysis zone showed that before the middle SDLP was lower when no gates were present ($F = 6.0$, $p = .018$; after the middle, Gates: $F = 1.0$, $p = .329$).

To summarize, SDLP was lower when no curves were present than when there were curves, both before and after the middle. Before the middle SDLP was lower when no gates were present but this difference disappeared once the driver had passed the middle. SDLP increased throughout the thoroughfare, except for thoroughfares without curves. The increase of SDLP throughout the thoroughfare was thus larger when no gates were present.

D. Effect of curves and gate constructions on workload

The MANOVA revealed no significant main effect for Curves ($F_{(2,44)} = 1.2$, $p = .321$) , Gates ($F_{(2,44)} < 1$, $p = .463$) or Analysis zone ($F_{(2,44)} = 2.4$, $p = .106$), however there was a significant interaction effect of Curves × Analysis zone ($F_{(2,44)} = 6.4$, $p = .004$).

Subsidiary univariate analyses for mean RT revealed a significant interaction effect for Curves x Analysis zone ($F_{(1,45)} = 12.8$, $p = .001$). Separate tests for each level of Analysis zone showed that after the middle, mean RT was slower when there were curves (M: 708.817, SD: 15.857) (no curves: M: 660.962, SD: 15.615) ($F = 14.5$, $p < .0005$; before the middle: $F = 1.2$, $p = .283$, no curves: M: 699.261, SD: 17.554, curves: M: 682.798, SD: 17.642). Separate tests for each level of Curves showed that when no curves were present, mean RT was slower before than after the middle ($F = 7.4$, $p = .009$). When curves were present mean RT was marginally faster before than after the middle ($F = 3.8$, $p = .057$).

Subsidiary univariate analyses for mean hit rate revealed no significant interaction effect for Curves x Analysis zone ($F_{(1,45)} = 1.3$, $p = .253$).

To summarize, the slower RT when curves were present after the middle of the thoroughfare showed that curves increased workload. Throughout the thoroughfare mean RT decreased when no curves were present and increased when curves were present. Mean hit rate was not affected by Gates or Curves.

3.1.7 Discussion and policy recommendations

A. Experience of road environment outside relative to inside urban area

With respect to research question 1, it was hypothesized that drivers would experience the road segment outside the urban area as monotonous relative to the more complex road environment inside the urban area. Faster mean RT and higher mean hit rate on the PDT outside the urban area indicated a lower workload level outside the urban area. This indeed confirms the hypothesis that drivers experienced the road segment outside the urban area as more monotonous and less complex than the thoroughfare. These results are in line with those obtained by Campagne et al. (2005), Cerezuela et al. (2004) and Thiffault and Bergeron (2003) that examined the phenomenon of 'highway hypnosis' by means of driver's visual behavior, EEG-data and steering wheel movements, respectively.

B. Effect of gate constructions on driving behavior and workload

Gate constructions only had a local speed reduction effect of 3 kph, i.e., from 97 m before to 97 m after the entrance. However, this lower speed was accompanied by a higher SDAD and a higher SDLP. The local speed reduction is in line with results by Charlton and O'Brien (2002) showing a speed reduction caused by a gate construction disappeared after 250 m. In addition, these authors showed a habituation effect of gates, as the local speed reduction effect diminished under repeated exposure. Galante et al. (2010) showed that gate constructions only had a speed reduction effect along the whole urban area when speed in the base scenario was high. In the base scenario with low speeds gate constructions reduced speed only in the vicinity of the entrance (deceleration started at 400 m before entrance). Concerning the 3 kph speed reduction in the direct vicinity of the gate construction, Elvik's Power Model for urban roads (Elvik, 2009, p. 58) estimates a decrease in fatal accidents with 16% to 17% and 8% for injury accidents. This road safety improvement is particularly important for road segments with an outspoken residential function (such as the ones we investigated), because vulnerable road users suffer even more severe injuries than car occupants with the same impact speed (Elvik, 2009, p. 50). It should be noted that the size of the speed reduction in other gateway studies (i.e., reductions between 5 and 24 kph) (Galante et al., 2010; M. Taylor & Wheeler, 2000) is larger than in our study (i.e., about 3 kph). This can be explained however, by the use of different speed limits in these studies since required speed reductions in the studies of Galante et al. and Taylor and Wheeler (i.e., from 90 kph to 50 kph) were much larger than in our study (i.e., from 70 kph to 50 kph). Although a direct and straightforward comparison with other types of TCM is rather difficult because of the differences in context and methodology, we note that the size of the speed reduction induced by our gate construction is rather small compared to the 20 to 25 kph (85th percentile) speed reduction produced by speed tables located at the beginning of cross-town roads (Moreno et al., 2011). However, the results of the field experiment conducted by Hallmark and colleagues (2007) (involving TCM such as transverse pavement marking, a speed feedback sign, a speed table, lane narrowing with centre island etc.) are more in line with our results. Furthermore, no evidence was found for the hypothesized complementary safety effects on mean speed of the local gate effect in the transition zone and the effect of curves in the through route. This finding adds to the existing discussion in the literature, as Taylor and Wheeler (2000) established that gate constructions complemented by additional measures in the through route were most effective, whereas the speed reduction inside the thoroughfare that was reported by Galante et al. (2010) was limited to only one direction of the thoroughfare. More research thus is necessary to resolve this issue of complementary effects of gates and curves.

The higher SDAD showed that acceleration and deceleration were more abruptly in the presence of gates. This effect was not limited to 194 m before and 282 m after the entrance gate, as it was still present somewhat further, i.e., before the middle of the thoroughfare. Yet, once drivers passed the middle of the thoroughfare, SDAD was not influenced anymore by the presence or absence of gate constructions. Although the local speed reduction can be considered as an improvement in terms of road safety, the increased SDAD indicate that speed monitoring is slightly less harmonious near the gate. However, according to our opinion, the increase is too small to expect road safety problems.

From 97 m before the gate till the middle of the thoroughfare, SDLP was higher when gates were present. It is worth noting that the increased SDLP was not the result of deviations outside the own driving lane or of the steering maneuver required to take the gate as these road segments were excluded from the analysis (see Figure 27). During the experiment, we saw that drivers orient the vehicle in direction of the gate which results in small swerving maneuvers within the own driving lane. According to our opinion, the increased variability is too small to expect road safety problems.

Mean RT and mean hit rate were not influenced by gate constructions which may be the result of the local effect of gate constructions.

To summarize the findings for research question 2, a reduction of mean speed induced by gate constructions can improve road safety, but the impact remains very local. At the same time, gate constructions can interrupt the homogeneity of the traffic flow and increase the variation of the vehicle's position within the driving lane. However, in the present study, these potentially negative effects are – according to our opinion – too small to expect road safety problems.

Altogether, the decision to implement gate constructions should always be determined by the broader situational context of the road segment under study and the main functionalities that have to be served by the through route. For thoroughfares with a predominant traffic function, the implementation of gate constructions will not necessarily improve road safety, because they disturb the homogeneity of the traffic flow. For thoroughfares with an outspoken residential function, speed reduction remains of capital importance. This however, should not prevent road designers and engineers to consider additional *forgiving* measures such as optimal radii, wider traffic lanes or recovery areas, when designing gate constructions. The implementation of some of these forgiving elements is illustrated in Figure 30.

Figure 30 Gate constructions with wider traffic lanes and recovery area ('Transportation Resources - Neighborhood Traffic Calming - Medians', 2011)

C. Effect of curves on driving behavior and workload

Throughout the urban area mean speed was about 1 kph lower when curves were present. However, this lower speed was accompanied by a higher SDAD and a higher SDLP. This indicates drivers manage the variations in speed less smoothly and are more inclined to wander out in a curved thoroughfare. It seems probable that the increased SDAD is directly related to the fact that drivers decrease their speed before entering a curve and accelerate again once leaving the curve. These speed fluctuations automatically lead to higher SDAD. The increased SDLP on the other hand probably reflects drivers' typical tendency for cutting, swinging or drifting and to adjust their steering angle while negotiating the curve (PIARC, 2003). Worth noting here is that the simulator vehicle's midpoint never exceeded the centre or edge line during the experimental trips. Multiple reasons can be found in order to further explain increased deviations within the driving lane, going from the level up to which divers are skilled in correctly assessing a difficult road section (e.g., Campbell et al., 2008), to factors such as in-vehicle distraction (Horrey & Wickens, 2004), text messaging (Crisler et al., 2008; Hosking et al., 2006), time of day (Lenné et al., 1997), impairment due to alcohol or drugs (Lenné et al., 2010), or sleepiness (Verster et al., 2011). Yet, even though this increased lateral displacement remains to be situated within the driving lane, negative side effects on road safety are still possible (De Waard, 1996; Ramaekers, 2003).

As for mean performance on PDT, only the mean RT was higher when curves were present, and this was limited to the road segment after the middle of the thoroughfare. This result indicates that drivers experienced a higher workload when driving along the curved thoroughfare. Under the condition that mental overload is avoided and workload level approaches the optimal level, the increased workload level in a curved thoroughfare may have a positive effect on driving behavior. An excessive increase in workload however should be avoided at all cost especially for novice and elderly drivers (Shinar, 2007).

These different results replicate findings reported in several earlier studies. Speed variations nearby curves have been investigated in many studies. Taragin (1954) suggested that drivers adjust their speed before entering a curve and keep it constant in a curve. Mintsis (1988) on the other hand observed lowest speed in the middle of the curve. The back-and-forth visual pattern, which was explored by Shinar et al. (1977) and Tsimhoni and Green (1999) showed that drivers need more visual information on a curved road. Among others, Laya (1992) found that the pattern of eye fixations, as a measure of workload, varies throughout the curve sequence. In addition, several studies demonstrated that increased workload in curves was highly dependent on several curve-related geometric characteristics such as curve radius and deflection angle as a measure of curve length.

In conclusion for research question 3 it can be concluded that curves can have both positive and negative effects on driving behavior. On the one hand, they induce lower mean speed while on the other hand they disturb traffic flow and engender a rather unstable lane position. The negative side effects could be compensated for if road designers would anticipate to the driver's potentially less accurate maneuvers and strive for so-called *forgiving roads* (Ogden, 1996). Forgiving roads are for instance characterized by optimal curve radii, wider traffic lanes and recovery areas. Also, curves can be helpful in avoiding mental underload. However, the risk of creating overload should always be kept in mind when designing curves as a measure for calming traffic in urban areas.

3.1.8 Limitations and future research

As indicated by Charlton (2007), the issue of external validity correctly arises when discussing the results of research employing driving simulations. Notwithstanding, previous studies have repeatedly proven that research employing driving simulations has several advantages. Besides the avoidance of potentially dangerous situations on the real road, there is the cost efficient and easy data collection (Kaptein et al., 1996; Charlton 2007, p. 883), the advanced level of control over a wide range of factors that otherwise would not be possible. Furthermore, several driving simulator experiments proved the suitability of advanced driving simulators as a tool to examine geometric design (Bella, 2009). Albeit that moving-base driving simulators provide a greater degree of realism and a more correct rendering of real driver behavior than fixed-base simulators (Bella, 2009) there are serious indications that fixed-base driving simulators are perfectly adequate to examine geometric design issues (Charlton, 2004 & 2007; Bella, 2007 & 2008; Keith et al., 2005; Federal Highway Administration, 2007; Calvi et al., 2012). In addition, the fixed-base simulator used in this study is equipped with a 180° field of view, which satisfies the prescribed minimum of 120° field of view for the correct estimation of longitudinal speed (Kemeny and Panerai, 2003). Moreover, this seamless curved screen avoids misalignment of the multiple displays which decreases the chance of simulator sickness (Fisher et al., 2011).

With respect to (the effect) of gate construction, further research could focus on different geometric design configurations. In addition, smaller and thus, more accurate analysis zones might provide more detailed insight into the effects of gate constructions. Currently, a driving simulator study is prepared to examine the durability of the effect of gates on driving behavior.

3.1.9 Conclusion

The paper investigates the effect of gate constructions located at the entrance of the urban area and horizontal curves within the urban area on driving behavior and workload.

The peripheral detection task (PDT) was used as an indicator for workload and showed that drivers experienced the road outside the urban area as less cognitively demanding relative to the more complex road environment inside the urban area. Whereas curves induced a speed reduction that was sustained throughout the entire urban area, variability of acceleration/deceleration and lateral position increased. In addition, PDT performance indicated higher workload when curves were present (versus absent). Gate constructions locally reduced speed (i.e., from 97 m before to 97 m after the entrance) and increased variability of acceleration/deceleration and lateral position nearby the entrance. However, the effects on SDAD and SDLP are too small to expect road safety problems.

It can be concluded that both curves and gate constructions can improve road safety. Notwithstanding, the decision to implement these measures will depend on contextual factors such as whether the road serves a traffic-, rather than a residential function. In addition, we advise to road designers to take the concept of *forgiving roads* into account.

3.2 DOES THE EFFECT OF TRAFFIC CALMING MEASURES ENDURE OVER TIME? – A SIMULATOR STUDY ON THE INFLUENCE OF GATES

This chapter is based on:

Ariën, C.; Brijs, K.; Brijs, T.; Ceulemans, W.; Vanroelen, G.; Jongen, E.M.M.; Daniels, S.; Wets, G. (2014) Does the effect of traffic calming measures endure over time? – a simulator study on the influence of gates. In *Transportation Research part F: Traffic Psychology and Behaviour, 22*, 63-75. doi: 10.1016/j.trf.2013.10.010. [web of science: 5 year impact factor 2.245]

Proceedings:

Ariën, C.; Brijs, K.; Brijs, T.; Ceulemans, W.; Vanroelen, G.; Jongen, E.M.M.; Daniels, S.; Wets, G. (2013). *Does the effect of traffic calming measures endure over time? – A simulator study on the influence of gates.* In: Proceedings of 4th International Conference on Road Safety and Simulation, Rome (Italy), October 23-25, 2013.

Abstract

Accident statistics show that transitions from rural to urban areas are accident prone locations. Inappropriate speed and mental underload have been identified as important causal factors nearby such transitions. A variety of traffic calming measures (TCM) near rural-urban transitions has been tested in field experiments and driving simulator studies. Simulator experiments repeatedly exposing participants to the same treatment are scarce, hence it is unclear to what extent the effects of a TCM endure over time.

This is precisely the objective of the current study: to examine what happens with the behavior of drivers when they are exposed multiple times to the same treatment (in this case a gate construction located at a rural-urban transition). Over a period of five successive days, seventeen participants completed a 17 km test-drive on a driving simulator with two thoroughfare configurations (gates present or absent) in a within-subject design. Results indicate that gates induced a local speed reduction that sustained over this five-day period. Even though participants were inclined to accelerate again once passed by this gate configuration, they always kept driving at an appropriate speed. We did not find any negative side effects on SD of acceleration/deceleration or SDLP.

Overall we conclude that gate constructions have the potential to improve road safety in the direct vicinity of rural-urban transitions, even if drivers are repeatedly exposed. Notwithstanding, we advise policy makers to appropriately use this measure. Best is to always carefully consider the broader situational context (such as whether the road serves a traffic- rather than a residential function) of each particular location where the implementation of a gate construction is one of the options.

Highlights

- Participants are repeatedly exposed to a gate construction in a driving simulator
- Gates induced a local speed reduction that sustained over the five-day period
- Participants accelerated again after the gate to continue close to the speed limit
- Standard deviation of acceleration/deceleration was not influenced by the gates
- Gates did not affect standard deviation of lateral position

3.2.1 Introduction

Experimental research shows that the transition from rural to urban areas is a serious problem in terms of road safety (Charlton, Alley, Baas & Newman, J. E. (2002), 2002; Galante, Mauriello, Montella, Pernetti, Aria & D'Ambriosio, 2010; Taylor & Wheeler, 2000). It is hypothesized that accidents near these transitions are largely caused by inappropriate speed (Hallmark, Peterson, Fitzsimmons, Hawkins, Resler & Welch, 2007; Charlton et al., 2002). Furthermore, mental underload and failure to maintain a proper lateral position are – besides many other – behavioral causative factors for accidents, especially in horizontal curves (Charlton, 2007). Insufficient driver alertness and the (unconscious) tendency to speed in turn, could be related to the combination of a changing road environment (the spatial and structural properties of rural areas are typically less complex than those of urban areas and probably generate less mental arousal) and a suddenly changing speed limit (i.e., typically from 70 kph to 50 kph) (Ariën et al., 2013a (paragraph 3.1); Forbes, 2011). Appropriately designed transition zones are therefore of crucial importance.

Previous field experiments and driving simulator studies examined the effect of a variety of traffic calming measures (TCM) on major cross-town roads. Forbes (2011) grouped the transition zone treatments into four categories: geometric design (e.g., chicanes or central islands), traffic control devices (e.g., variable message signs or speed cameras), surface treatments (e.g., speed humps or transverse rumble strips) and roadside features (e.g., as gateways or landscaping).

In general, the surrounding context and the type of measure have a large influence on the established results (Forbes, 2011). The County Surveyor's Society (1994) analyzed 24 village traffic calming schemes and obtained mean speed reductions between 2 kph and 16 kph, which resulted in a decrease of all injury accidents and fatal/serious injury accidents by about 25% and 50% respectively. The Federal Highway Administration (2009b) reported speed reductions up to 24 kph in France, Denmark and the UK. However, speed reductions of 8-10 kph appear to be more typical (Department for Transport, 1993). Hallmark et al. (2007) examined seven low-cost TCMs in a before-after field experiment (data collection at 1-, 3-, 6-, 9- and 12-month intervals) and obtained changes in 85th percentile speed from -14 kph to +6 kph. However, a detailed look at the results showed that, while the speed reduction effect of some TCMs sustained over time or even increased, other speed reductions diminished under repeated exposure. This 'habituation' effect is also reported by Charlton and colleagues (2002).

Various driving simulator studies (e.g. Ariën et al., 2013a (paragraph 3.1); Dixon et al., 2008; Federal Highway Administration, 2010; Galante et al., 2010; Molino et al., 2010) reported speed reductions from 3 kph to 17 kph for TCMs in the transition zone. Important to notice is that the results of Dixon et al. (2008), Galante et al. (2010) and Ariën et al. (2013a) (paragraph 3.1) all indicate that these speed reductions are limited in terms of distance along the road. Generally, speed reductions stretch out from 97 m before to 400 m after the TCMs studied, thus covering not much more than the nearby vicinity. Overall, transition zone treatments complemented with measures further along the through route are most effective (Forbes, 2011; Harkey & Zegeer, 2004; M. Taylor & Wheeler, 2000).

Although the main purpose of a TCM is the reduction of driving speed, we aim to investigate both longitudinal and lateral driving parameters because we want to approach driving behavior as a multi-dimensional, rather than a single-dimensional concept (RISER, 2005; Rosey et al., 2008). The way in which drivers manage their speed mostly applies to the longitudinal dimension. Mean speed is often used as a measure for safe driving because of its positive relation with crash risk and severity (European Commission, 1999; Safetynet, 2009b; Shinar, 2007). The acceleration noise, defined as the standard deviation of longitudinal acceleration and deceleration (SDAD), is a good indicator for the degree to which drivers are able to keep speed fluctuations under control (Ko, Guensler, & Hunter, 2010) and gives an indication for the smoothness of the traffic flow (Tapani, 2012). An abrupt speed change might disrupt the traffic flow and decreases the time to anticipate and/or react, which might in turn result in an increased risk for rear-end collisions. Af Wåhlberg (2000, 2004, 2006) found some support for a positive relation between driver acceleration behavior and accident rates. The lack of a harmonized horizontal position of the vehicle within the driving lane is one of the primary factors in single-vehicle run-off the road accidents and head-on collisions and refers thus to the lateral dimension of driving performance (Rosey et al., 2008; Verster & Roth, 2011). The standard deviation of the lateral position (SDLP) is often used as an indicator for lateral trajectory control or the amount of 'weaving' of the car (Verster & Roth, 2011).

The advantage of field experiments is that they collect speed measurements for a large number of vehicles over an extended period of time. However, they are costly and not without methodological constraints because there is no control over factors such as weather and traffic conditions. Different from that, driving simulators provide researchers with total control over the various driving conditions that matter. In addition, simulator experiments are safe and cost efficient and a variety of driving performance data can be collected at a continuous high rate (L. Nilsson, 1993; Rudin-Brown et al., 2009). Notwithstanding, according to Jamson and Lai (2011) "*the simulator community should – amongst the usual challenges of simulator validity, participant self-selection and simulator sickness – also consider the potential influence of novelty effects on driving performance data*". As for the latter, Shinar (2007, p. 763) describes a novelty effect as the phenomenon where "*people's reactions are more extreme to new systems than to existing ones*".

Evidently, such novelty effects do not only apply to the simulator systems themselves, but also to the specific treatments (for instance TCMs) being tested. Interestingly however, most of the simulator experiments carried out exposed participants only once to the treatment under investigation. Authors often acknowledge this as an important limitation to their results since indeed, it remains unclear what would happen with the treatment effects found in case participants would be exposed repeatedly to the same treatment (e.g. Ariën et al., 2013; Charlton, 2007; Comte & Jamson, 2000; Jamson, Lai & Jamson, 2010; Kircher, 2007). To the best of our knowledge, there is only a handful of simulator experiments exposing subjects multiple times to an identical treatment. Roughly, these can be subdivided into two groups.

A first group of studies, exposed participants several times to the same treatment by means of one single simulator session. For example, in the study by Jamson and Lai (2011) each participant passed the same TCM four times in a single session consisting of two test trips. A comparable study set-up was used by Brown (2001) and Lewis-Evans and Charlton (2006). They exposed subjects quite intensively to a new in-vehicle lane departure warning system (30 min) and to different road widths (25 km) respectively in order to find out if ‘getting used’ to these treatments would induce so-called ‘behavioral adaptation’ effects.

A second collection of studies also exposed participants several times to the same treatment but by means of multiple simulator sessions spread over different days, instead of one single session only. For instance, Manser and Creaser (2011) investigated the effect of a rural intersection support system on drivers’ behavior and made participants drive 12 times a day for a period of five days with the system turned on at days 2, 3 and 4. Jenssen et al. (2007) examined an adaptive front light system within a study design where each test- and control participant had to complete one driving session per day for a period of six consecutive days. We are aware that more simulator studies have been published where participants had to complete multiple driving sessions and thus were repeatedly exposed to a (highly) identical driving scene (Åkerstedt, Ingre, Kecklund, Anund, Sandberg, Wahde et al., 2010; Charlton & Starkey, 2011; Domeyer, Cassavaugh & Backs, 2013; Lenné, Triggs & Redman, 1997; Martens & Fox, 2007). Yet, the focus of interest in these studies is too different from ours which is to test the impact of road infrastructural treatments on driver behavior. Since they fall outside the scope of this paper we limit ourselves to just mentioning them.

To summarize, when it comes to testing the impact of infrastructural and/or technological treatments on drivers’ behavior under conditions of repeated exposure, the literature available is rather scarce. Turning more specifically to road infrastructural TCMs, the study by Jamson and Lai (2011) is the only reference we are knowledgeable of. This brings us to the main objective of this paper and the more specific research questions being addressed.

3.2.2 Objective & research questions

The present study will investigate the effect of gate constructions at rural-urban transitions on the driving behavior of a sample of participants that will be repeatedly exposed to this specific type of TCM. We formulate the main research questions as follows:

1. Do gate constructions at a rural-urban transition influence driving behavior?
2. How far in distance along the road does the influence of gate constructions at a rural-urban transition reach?
3. Does the effect of gate constructions at a rural-urban transition change when the same subjects are repeatedly exposed?

3.2.3 Methodology

A. Participants

Twenty-nine volunteers with a full driver's license participated in the study. They were recruited via e-mail at Hasselt University and at XIOS University College. Twelve participants were excluded: three did not finish the experiment due to simulator sickness, eight participants could not complete the five experimental days due to technical problems and one participant was identified as outlier (drove during more than 25% of the analysis section faster than three inter-quartile distances from the group's mean). Thus, 17 participants (9 men) remained in the sample (mean age: 27.2; SD age: 11.6). All gave informed consent and had (corrected to) normal vision. Age and gender were not taken into account as between-subject factors in the statistical analysis.

B. Apparatus

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-base (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual and auditory feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images and depiction of the speedometer. Three projectors offer a resolution of 1024 x 768 pixels and a 60 Hz refresh rate. The sounds of traffic in the environment and of the participant's car were presented. The data, which was collected at a 60 Hz frame rate, was interpolated to a 1 m distance interval before starting the data analysis.

C. Simulation scenario

The 17 km driving scenario contained two thoroughfares, alternated with filler pieces (see Figure 31). One rural-urban transition contained a gate construction while the other had no additional treatments to mark the transition zone. Figure 32 gives an overview plan of the thoroughfare and a screenshot of the simulator view.

Both thoroughfares had a length of 1270 m and were equipped with signs marking the beginning of the urban area and the 50 kph speed limit. In each thoroughfare, four intersections with right of way and accommodated by zebra crossings were alternated with four horizontal curves (40° left curves and 30° right curves with a curve length of 100 m). The ribbon development (Albrechts, 1999), present 200 m before and after the thoroughfare, merged into a stretch of continuous buildings inside the urban area. The road approaching to and inside the urban area was divided in two lanes (3.25 m width) with one lane per travel direction. The cycle lanes were separated from the traffic lanes by a parking strip inside the urban area and by a green strip outside the urban area.

Gate constructions with non-parallel axis displacement and central island were located just after (entrance gate) and before (exit gate) the border signs of the urban area in the thoroughfare with gates. In this study we focus on the entrance gate because this gate is located at the high-to-low speed transition. The geometric design of the gate construction is based on CROW (2004, p. 812) and is illustrated in Figure 32b. According to CROW (2004) this type of gate construction is the best alternative besides a roundabout and a parallel axis displacement.

The two thoroughfares were alternated with rural filler pieces (see Figure 31). They were different from the thoroughfares with respect to design, speed limit (variations of 70 kph and 90 kph and a short segment of 30 kph and 50 kph) and surrounding environment and meant to provide some variation while driving. In addition, the filler pieces were used to provide some variety in the driving scene as well as in the interaction with other road users. In order to prevent interference from these small day-to-day variations the last kilometer before the analysis zone of the urban area was always standardized. Weather conditions were sunny and dry.

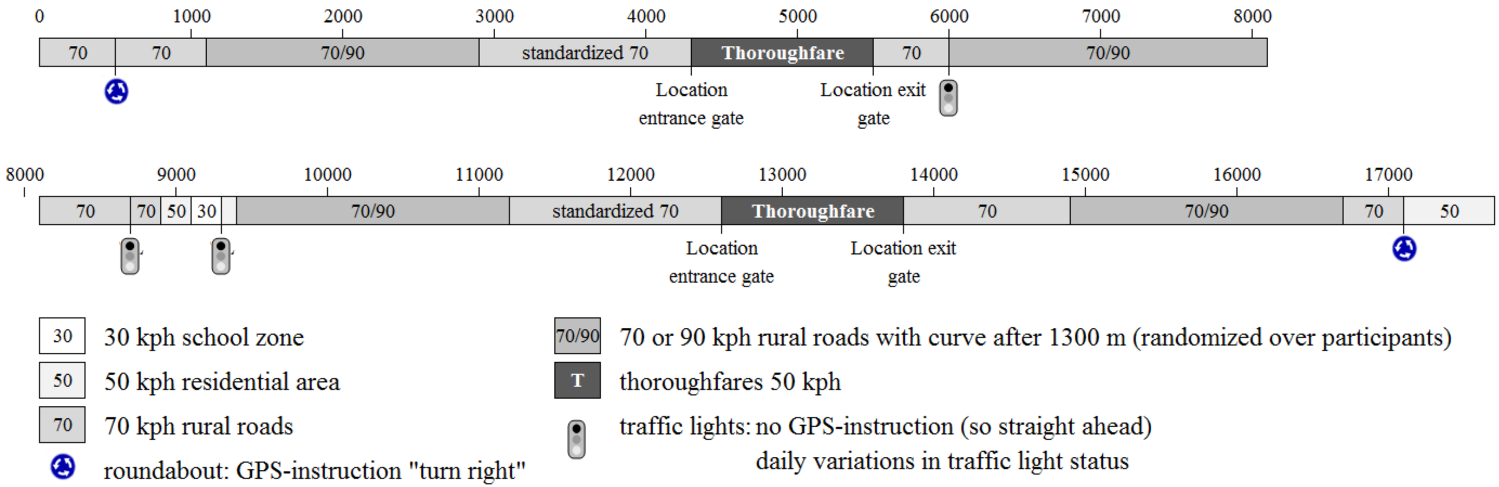
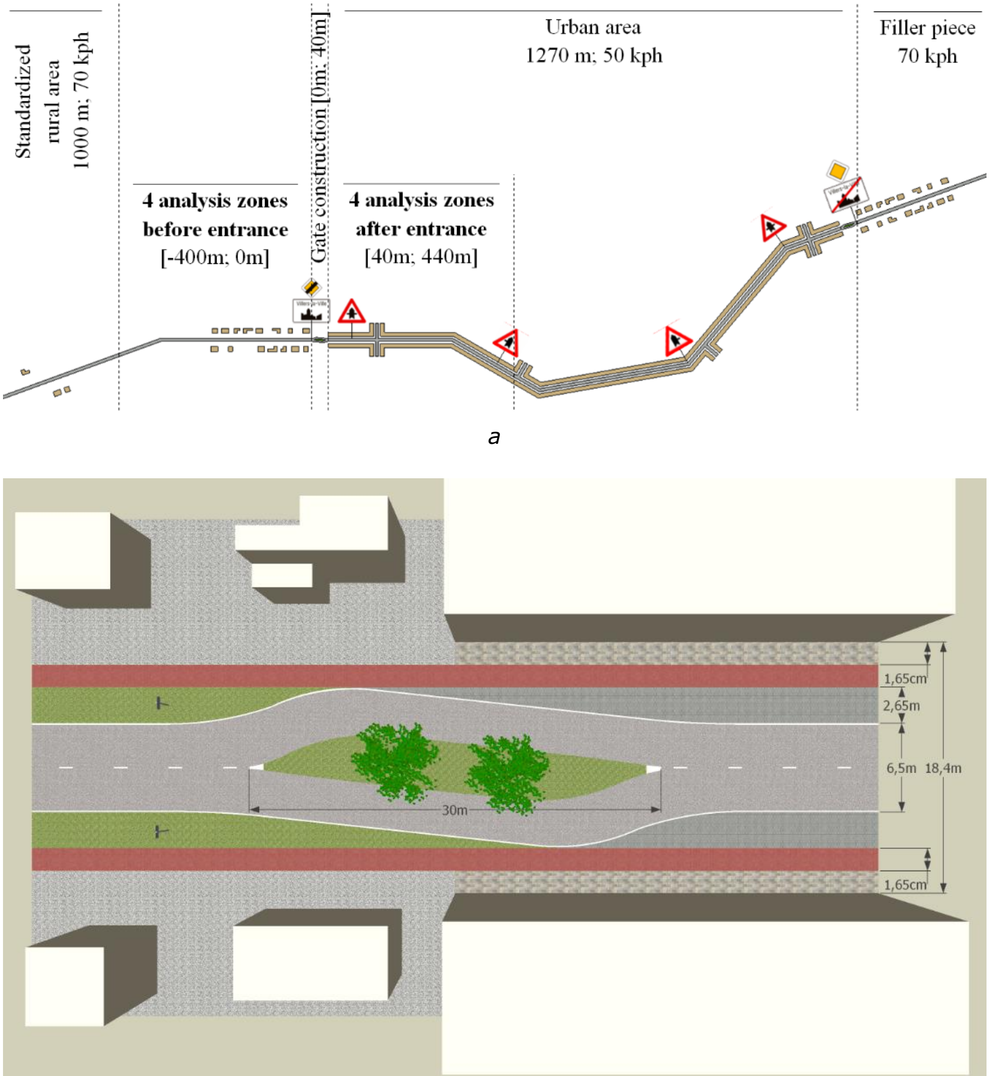


Figure 31 Plan view of the daily test drive



b

Figure 32 Plan view of (a) the transition zone and thoroughfare; and (b) the gate construction

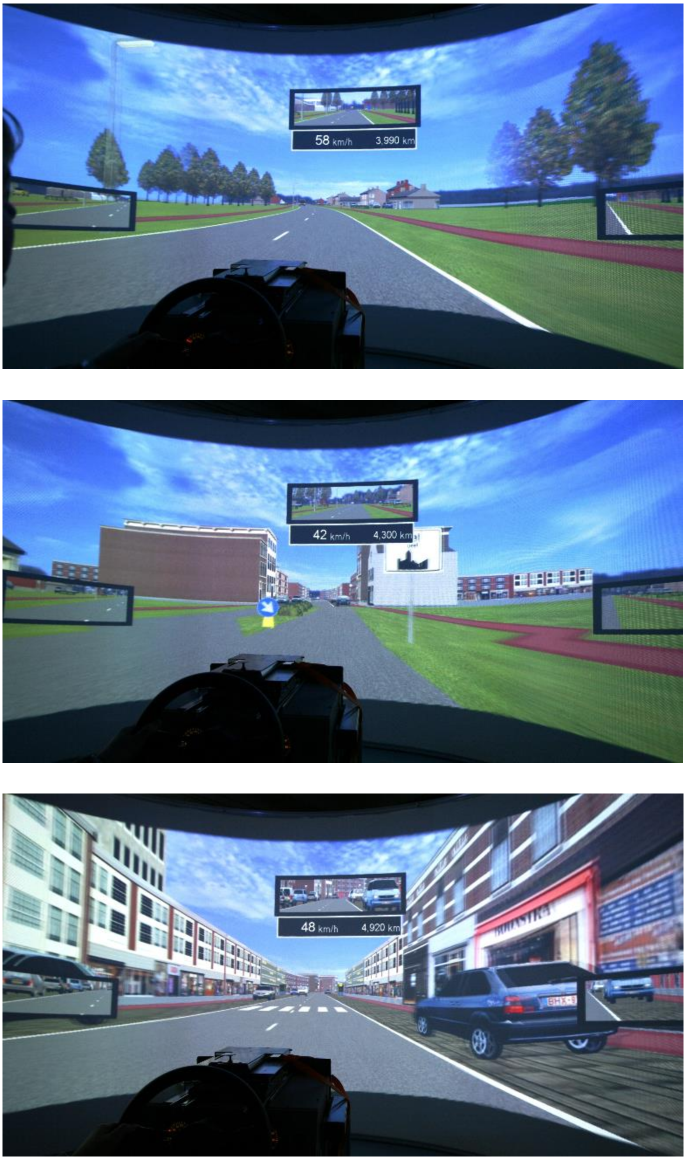


Figure 33 A simulator view of a rural road section, the rural-urban transition with gate construction and an urban area section

D. Procedure

Subjects agreed to participate for a period of five consecutive weekdays. On the first day, participants were asked for their informed consent and to fill out a form with their personal data (e.g. date of birth, gender). After a general introduction in the driving simulator, a practice session with two scenarios (4 km rural road with some slight curves; 7 km with successively a motorway, a 70 kph rural road and an urban area equipped with a gate construction at the rural-urban transition) followed in order to get acquainted with the simulator. Afterwards, participants drove the 17 km test drive in which they passed two thoroughfares (i.e., once with and once without the gate constructions) in a counterbalanced order. During the next four days, participants drove the same 7 km practice scenario followed by the 17 km test drive. The order of 'with or without' gate did not change during the whole experiment for a particular participant because the purpose of this study was to examine driving behavior of participants who were repeatedly exposed to the gate construction in the same configuration.

Subjects were instructed to drive as they normally would in their own car and to apply the traffic laws as they would (or would not) do in reality. A GPS voice gave the necessary route guidance instructions.

E. Data collection and analysis

Measures for longitudinal and lateral control were recorded by the simulator. Mean speed [kph] is a typically selected indicator for safe driving (Safetynet, 2009b) as well as standard deviation of longitudinal acceleration/deceleration (SDAD) [m/s²] which gives a good indication for the extent to which drivers are able to keep speed variations under control (Marchesini & Weijermars, 2010). Lateral trajectory control is analyzed by means of the standard deviation of the lateral position (SDLP) [m].

Data analysis for these three dependent measures is based on 8 successive analysis zones of 100 m (4 outside and 4 inside the urban area), starting at 400 m before the entrance of the urban area and ending at 440 m after the entrance (see Figure 32a). The 40 m road segment containing the gate construction itself (i.e., [0 m; 40 m]) was excluded from the analysis. Therefore, a 2 (gate) × 5 (day) × 8 (analysis zone) within-subject multivariate analysis of variance (MANOVA) was conducted on mean speed, SDAD and SDLP to provide an overall measure of driving performance as a function of the experimental conditions. Additional post-hoc univariate tests and ANOVA's were performed and *p*-value was set at 0.05 to determine statistical significance.

Kolomgorov-Smirnov tests showed that the data was not always distributed normally. However, statistical analyses with transformed data (by means of the square root transformation) showed very similar results compared to the results of the non-transformed data. In addition, Field (2009, p 360) states that "*when group sizes are equal [which is the case in this study] the F-statistic can be quite robust to violations of normality*" and Meyers, Gamst and Guarino (2013, p 72) argues that a transformation improves the precision of a MANOVA but can also lead to serious problems in terms of the interpretation of the results. Therefore we decided to present the original (non-transformed) data.

3.2.4 Results

The multivariate and univariate statistics are reported in Table 11. The results of the MANOVA showed a significant main effect of *Zone*. In addition the interactions of *Gate × Analysis zone* and *Day × Analysis zone* have a significant effect on mean speed, SDAD and SDLP. The complete understanding of the significant interactions requires univariate analyses in which each dependent variable is considered separately. There was no significant effect of the factor *Gate* or *Day* on the dependent variables.

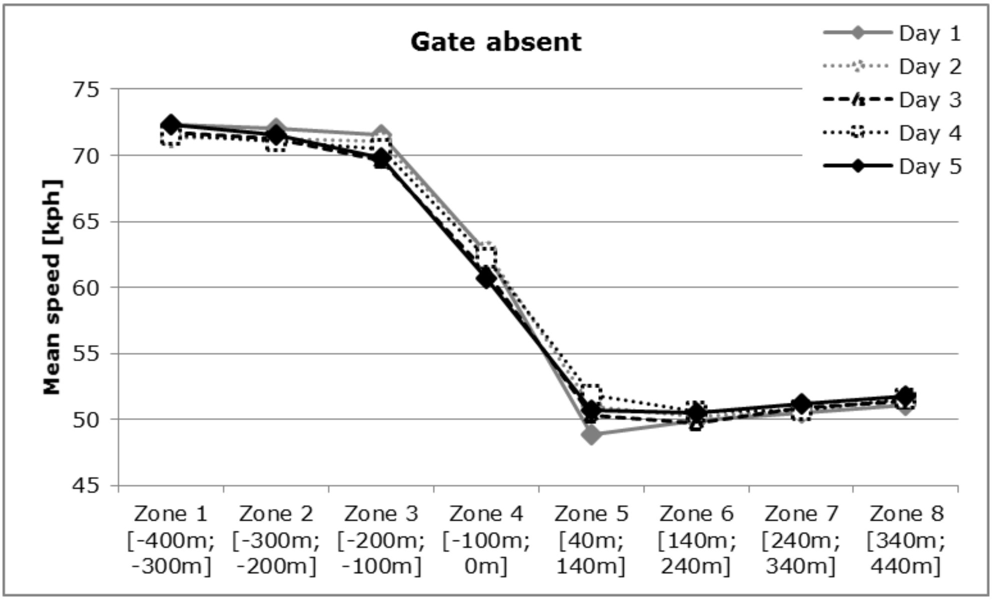
Table 11 Multivariate and univariate statistics (significant p-values are indicated in bold)

Manova				
Variable	*Wilks' Lambda*	*F (dfs)*	*p*	*Partial eta squared*
Gate	0.734	1.7 (3, 14)	0.214	0.266
Day	0.795	1.2 (12, 164)	0.260	0.074
Analysis zone	0.007	69.3 (21, 316)	**<.001**	0.808
Gate × Day	0.825	1.0 (12, 164)	0.419	0.062
Gate × Analysis zone	0.423	5.3 (21, 316)	**<.001**	0.249
Day × Analysis zone	0.703	2.0 (84, 1335)	**<.001**	0.111
Gate × Day × Analysis zone	0.814	1.1 (84, 1335)	0.198	0.066

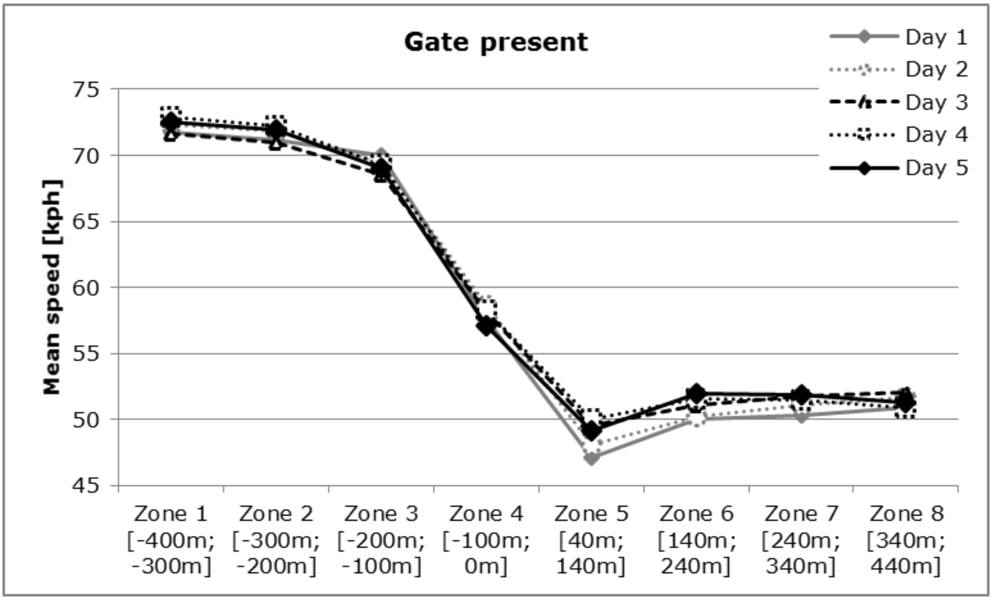
Univariate statistics (Greenhouse-Geisser)			
Variable	*F (dfs)*	*p*	*Partial eta squared*
Mean speed			
Analysis zone	400.5 (2, 35)	**<.001**	0.962
Gate × Analysis zone	16.1 (3, 47)	**<.001**	0.501
Day × Analysis zone	1.7 (7, 118)	0.120	0.094
SDAD			
Analysis zone	37.0 (1, 24)	**<.001**	0.698
Gate × Analysis zone	1.0 (2, 31)	0.408	0.054
Day × Analysis zone	3.6 (4, 71)	**0.007**	0.185
SDLP			
Analysis zone	8.8 (3, 55)	**<.001**	0.356
Gate × Analysis zone	2.2 (4, 59)	0.079	0.123
Day × Analysis zone	1.0 (8, 122)	0.631	0.045

A. Mean speed

Figure 34 shows the daily values for mean speed in each of the eight analysis zones and separated for the condition without (left graph) and with (right graph). As can be seen, drivers started to decelerate from 300 m before the entrance urban area until the first 100 m after the entrance after which they continued close to the speed limit (50 kph). Overall, mean speeds seem to be lower in the vicinity of the entrance of the urban area when a gate was present. Although the daily differences in mean speed seems to be limited, the graph for the condition 'gate present' give some indication for an increase in mean speed after passing the gate as the days progressed.



a

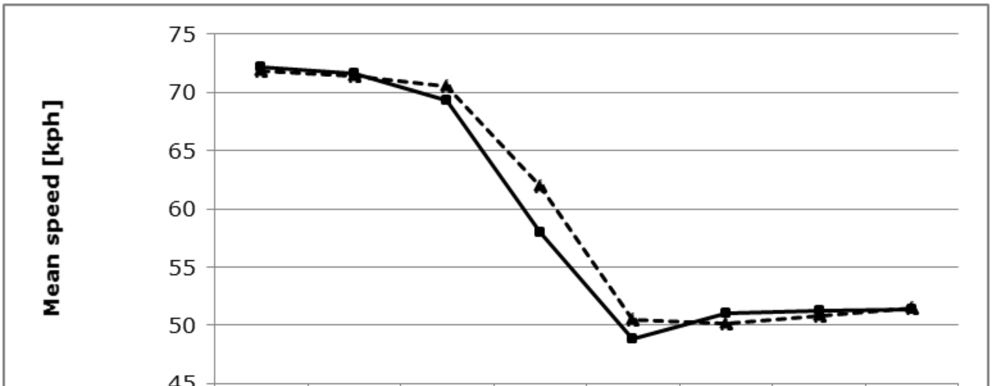


b

Figure 34 Mean speed as a function of Gate × Day × Zone (a) Gate absent and (b) Gate present (Gate construction was located between 0 m and 40 m)

The ANOVA for mean speed showed a significant main effect of *Analysis zone* and interaction effect of *Gate* × *Analysis zone*. Since there was no significant interaction between the factors *Day* and *Gate* or between the three factors, we can conclude from the significant interaction of *Gate* × *Analysis zone* that mean speed varied across the different analysis zones in function of the presence or absence of a gate construction, but not in function of the day. This means that the effects generated by a gate construction on a certain day were not significantly different from the other four days and that the indication, based on Figure 34, that mean speeds seemed to increase after passing the gate as the days progressed was not significant.

Figure 35 shows values for mean speed in each of eight analysis zone, separated for the condition with or without gate but irrespective of the day. Post-hoc analysis showed that mean speed was 1.2 kph to 4 kph lower from 200 m before the entrance of the urban area to 100 m after the entrance when a gate was present (zone 3: $F_{(1,\,16)}$ = 7.9, p = 0.012, partial eta squared η_p^2 = 0.332; zone 4: $F_{(1,\,16)}$ = 20.8, p < .001, η_p^2 = 0.565; zone 5: $F_{(1,\,16)}$ = 7.4, p = 0.015, η_p^2 = 0.315). In spite of this major speed reduction, participants slightly accelerated again between 100 and 200 m after the gate to a mean speed which was higher than when there was no gate construction present ($F_{(1,\,16)}$ = 7.8, p = 0.013, η_p^2 = 0.328). From 200 m after the entrance of the urban area, there were no significant differences in mean speed between the condition with or without gate.

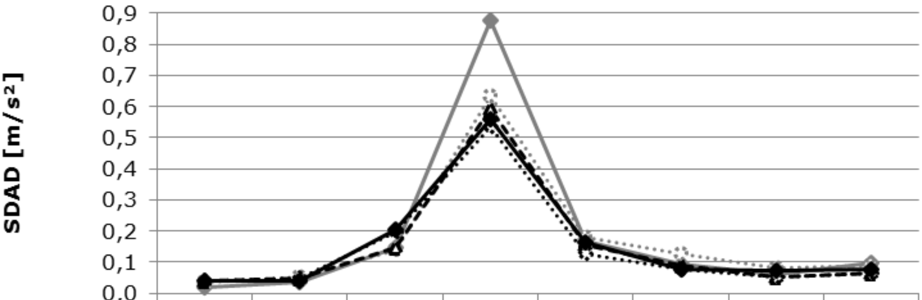


	Zone 1 [-400m; -300m]	Zone 2 [-300m; -200m]	Zone 3 [-200m; -100m]	Zone 4 [-100m; 0m]	Zone 5 [40m; 140m]	Zone 6 [140m; 240m]	Zone 7 [240m; 340m]	Zone 8 [340m; 440m]
No gate	71,9	71,4	70,5	61,9	50,5	50,2	50,8	51,5
Gate	72,2	71,6	69,3	57,9	48,8	51,0	51,3	51,4

Figure 35 Mean speed for the interaction of Gate × Analysis zone (Gate construction was located between 0 m and 40 m)

B. Standard deviation of longitudinal acceleration/deceleration (SDAD)

Figure 36 contains one plot per day, representing values for SDAD that where first averaged over the absence or presence of a gate and subsequently set out over the eight analysis zones. The graph shows a general increase during the last 100 m before the entrance of the urban area and that this increase was larger on the first day.



	Zone 1 [-400m; -300m]	Zone 2 [-300m; -200m]	Zone 3 [-200m; -100m]	Zone 4 [-100m; 0m]	Zone 5 [40m; 140m]	Zone 6 [140m; 240m]	Zone 7 [240m; 340m]	Zone 8 [340m; 440m]
Day 1	,019	,036	,147	,877	,168	,096	,061	,096
Day 2	,037	,053	,139	,633	,181	,127	,083	,088
Day 3	,040	,047	,149	,592	,157	,091	,051	,063
Day 4	,040	,047	,198	,535	,125	,079	,054	,067
Day 5	,042	,042	,204	,561	,164	,078	,073	,079

Figure 36 SDAD for the interaction of Day × Analysis zone (The entrance of the urban area was located at 0 m)

A main effect of *Analysis zone* and an interaction of *Day* × *Analysis zone* was revealed by the univariate tests for SDAD, resulting in values for SDAD which varied across the different analysis zones in function of the day. Because there was no significant main or interaction effect with the factor *Gate* we can conclude that the variations in SDAD were independent of the absence or presence of a gate. This was the reason why the values for SDAD were averaged over the factor *Gate* in Figure 36. The post-hoc analysis confirmed the findings based on Figure 36 that SDAD increased during the ultimate 100 m before the entrance of the urban area (i.e., zone 4). However, this increase was significantly higher on the first day compared to the other four days ($F_{(2, 36)} = 5.9$, $p = 0.005$, $\eta_p^2 = 0.268$).

C. Standard deviation of the lateral position (SDLP)

Subsidiary univariate tests for SDLP revealed only a significant main effect of *Analysis zone*. An overview of the SDLP per analysis zone can be found in Figure 37. It is important to note that these values were averaged over the five days and are irrespective of the presence or absence of a gate. The graph indicates that SDLP increased in road sections where participants had to pass a curve (i.e., zone 2, 7 and 8) and nearby the entrance of the urban area (i.e., zone 4 and 5) compared to the relative straight road sections without important variations in the road environment (i.e., zone 1, 3 and 6).

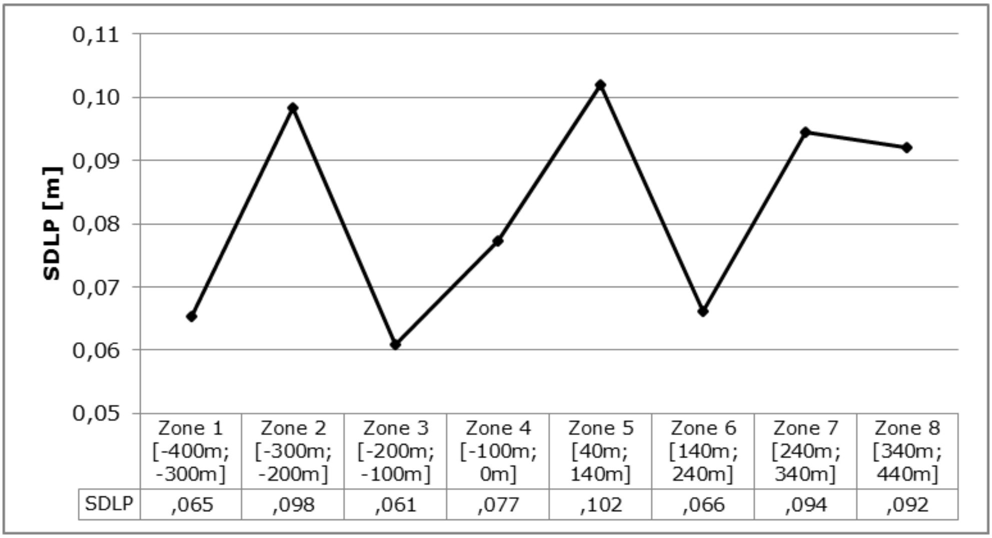


Figure 37 SDLP and the 95% confidence intervals for the main effect of Analysis zone (The entrance of the urban area was located at 0 m)

Post-hoc analysis showed that the values for SDLP varied significantly between the successive analysis zones ($F_{(3, 55)} = 8.8$, $p < .001$) , except in the last two (i.e., between zone 7 and zone 8): between zone 1 and 2: $p < .001$, between zone 2 and 3: $p < .001$, between zone 3 and 4: $p = 0.005$, between zone 4 and 5: $p = 0.011$, between zone 5 and 6: $p < .001$, between zone 6 and 7: $p = 0.004$, between zone 7 and 8: $p = 0.815$. The directions of these variations are clearly visualized in Figure 37.

3.2.5 Discussion

Mean speed, SDAD and SDLP were analyzed to find out (1) whether a gate construction located at a rural-urban transition influences driving behavior; (2) how far the influence reaches and (3) whether the effect would change when the same subject is repeatedly exposed during a period of five days.

The MANOVA showed a significant effect of *Zone*, *Gate* × *Zone* and *Day* × *Zone*. Since there was no significant interaction between the factors *Day* and *Gate* or between the three factors *Gate* × *Day* × *Zone*, we can conclude that the potential influence of a gate construction on driving behavior is independent of the day. This means that the effects generated by a gate construction on driving behavior on a certain day were not significantly different from the other four days. The univariate statistics revealed that the absence or presence of a gate had only an influence on mean speed. SDAD varied across the different analysis zones in function of the day and SDLP fluctuated across the analysis zones but these variations were independent of the day or the presence or absence of a gate.

Results for **mean speed** showed that the gate only had a local speed reduction effect from 200 m before to 100 m after the entrance of the urban area with speed reductions between 1.2 kph and 4 kph. For speed reductions of that size, Elvik's Power Model for urban roads (R. Elvik, 2009, p. 58) estimates a decrease in fatal accidents and injury accidents up to 12% and 8% respectively. The established speed reductions are in line with the 3 kph speed reduction obtained by Ariën et al. (2013a) (paragraph 3.1). The different speed limits used in the studies by Galante et al. (2010) and Taylor and Wheeler (2000) (i.e., from 90 kph to 50 kph instead of from 70 kph to 50 kph) might be an explanation for the fact that the size of the speed reductions in their gateway studies (i.e., reductions between 5 kph and 24 kph) is larger than in our study. The speed reductions generated by some of the TCMs investigated by Hallmark et al. (2007) are closer to our results (e.g. speed changes (V_{85}) of transverse pavement markings: -2 to 0 kph, a speed table: -5 to -4 kph and lane narrowing with center island using tubular markers: -3 to 0 kph).

The fact that the speed reduction effect of the gate is restricted to the direct vicinity of the entrance of the urban area is in line with previous field and simulator experiments in which speed reductions did not reach beyond 97 m (Ariën et al., 2013a) (paragraph 3.1), 250 m (Charlton & O'Brien, 2002) or 400 m (Galante et al., 2010: only in the base scenario with low speeds) after the gate.

Because the speed reduction effect established in this experiment was independent of the day, we can conclude that the speed reduction will preserve over a time period of at least five days. This is in line with the results of the longitudinal driving simulator experiment by Jamson and Lai (2011) where "*initial behavior is predictive of future behavior*" for countdown signs and hazard marker posts.

After the speed reduction generated by the gate, participants slightly accelerated again between 100 and 200 m after the gate to a mean speed that was higher than when there was no gate present. However, after this slight acceleration, participants continued at the same speed than when there was no gate present (i.e., close to the speed limit of 50 kph). The fact that drivers accelerate after the gate resembles a so-called 'kangaroo' effect which also has been discovered near the treatment zones of speed cameras (Safetynet, 2009b; Thomas, Srinivasan, Decina, & Staplin, 2008). The driving simulator study of Molino et al. (2010) also showed that mean speed increased again in the middle of the town after passing a chicane at the beginning of the city center. According to Safetynet (2009b), there is however no scientific evidence that such a 'kangaroo' effect leads to (more) dangerous situations or accidents.

Even though not influenced by the gate construction, **SDAD** increased during the last 100 m before the entrance of the urban area, and this rise was significantly larger on the first day compared to the other four days. It is highly probable that the increased SDAD relates to drivers having to decelerate from 70 kph to 50 kph when entering the urban area. This rather abrupt deceleration maneuver during the last 100 m before the entrance of the urban area is required to make the final deceleration in order to reach the 50 kph speed limit inside the urban area. Charlton et al. (2002, pp. 342-343) confirm that "*many motorist appear to find it difficult to slow down from highway or open road speeds to a slower speed when entering an urban or semi urban area*".

The fact that variations in acceleration and deceleration where significantly higher during the last 100 m before the entrance on the first day compared to the other days might suggest that participants were not yet fully adapted to handle the brake and gear pedals very precisely on the first day. Yet, participants were given the opportunity to familiarize with the simulator controls by means of a 10 min practice session (two trips of 4km and 7km respectively), which is in line with numerous other driving simulator studies (e.g., Bella, 2007; Calvi, Benedetto, & De Blasiis, 2012; Charlton, 2007; Galante et al., 2010; Montella et al., 2011).

Finally, we found variations in **SDLP** across the successive analysis zones which were independent neither of the day, nor of the presence or absence of the gate. Higher values for SDLP give an indication for more 'weaving' of the car (Verster & Roth, 2011) whereas lower SDLP-values are associated with a more harmonized position of the vehicle within the driving lane.

Figure 37 showed three comparable peaks in SDLP. The first (zone 2) and final (zone 7 and 8) peak values in SDLP can be explained by the presence of two slight curves (see Figure 32a). Several studies (e.g., Spacek, 2005; Charlton, 2007; Aubertlet, Pacaux, Anceaux, Plainchault & Rosey, 2010) established that drivers experience difficulties in maintaining a relatively constant lane position in curves and associated this with an increased accident risk for run-off the road accidents and head-on collisions. The increased values nearby the rural-urban transition (zone 5 and to a lesser degree in zone 4) can be related to multiple factors such as the increased complexity of the road environment and the presence of parked vehicles on the parking lane. This is in line with de Waard (1998) who associated higher SDLP-values with an increased mental workload.

Finally, it is noteworthy that, in the first two 100 m zones after the standardized kilometer (i.e., zone 1 and 2), mean speed, SDAD or SDLP did not significantly differ between approaching an urban area with or without gate or between the five days. Based on these results, we can assume that driving behavior after the standardized kilometer was not affected by the daily variations in road sections before this standardized kilometer and that participants approached the transition to the urban area every day in a similar way.

3.2.6 Limitations and future research

Although we are unable to pronounce upon the long term effect of this gate construction as in a before-after field experiment, this experiment provided the opportunity to examine driving performance during five successive days. Based on these results, we tried to anticipate the potential influence of novelty effects of a gate construction on driving performance data and find out whether the effect of gate constructions change when the same subjects are repeatedly exposed. In addition, it is worth mentioning that this experimental setup is – besides the study of Jamson and Lai (2011) – quite unique compared to the 'common practice' in driving simulator research in which each participant is exposed only once to the treatment under investigation.

External validity is an issue that often arises when discussing the results of a driving simulator experiment. Although moving base simulators provide a more correct rendering of real driving behavior and a greater degree of realism (Bella, 2009), there are strong indications that geometric design issues are examinable in fixed-base driving simulators in a perfectly adequate way (e.g., Bella, 2007, 2008; Calvi et al., 2012; Charlton, 2004; Federal Highway Administration, 2007). In addition, the seamless curved screen with a 180° field of view used in this study satisfies the prescribed minimum of 120°field of view for the correct estimation of longitudinal speed (Kemeny & Panerai, 2003).

Future research on gate constructions could focus on different geometric design configurations or the influence of complementary TCMs along the thoroughfare. In addition, a naturalistic driving experiment in which a sample is observed during a longer time period might also reveal interesting results. Furthermore, novelty effects in driving simulator research should receive more attention. To gain more insight in this effect, one could compare the results of this experiment with a driving simulator experiment in which each participant will be exposed several times in a single simulator session to the TCM, thus comparable with the study of Jamson and Lai (2011).

3.2.7 Conclusion and policy recommendations

The paper has investigated the effect of gate constructions at rural-urban transitions on the driving behavior of a sample of participants who were repeatedly exposed to this specific type of traffic calming measure. The study has established that the central island with non-parallel axis displacement had an influence on mean speed, but not on SDAD or SDLP. More specifically, a gate construction generated a significant speed reduction (i.e., 1.2 kph to 4 kph) between 200 m before to 100 m after the entrance of the urban area. Even though participants were inclined to accelerate again once passed by this gate configuration, they always kept driving at an appropriate speed, i.e., close to the imposed limit of 50 kph. In addition, these results for mean speed sustained over the five-day experimental period. In conclusion this study overall indicates that gate constructions have the potential to improve road safety in the direct vicinity of rural-urban transitions, even if drivers are repeatedly exposed.

Based on this outcome we advise (local) policy makers to at least consider gate constructions such as the one examined in this study as a potential traffic calming measure at rural-urban transitions with an increased accident risk. It goes without saying that with regard to the installation of such a gate, different aspects have to be taken into account in order to make this measure effective. For instance, in order to avoid frontal collisions, gate constructions should always be clearly visible and marked if necessary. Also, it should be avoided that drivers are required to execute (too) difficult steering wheel movements when they come along gates. Finally, the implementation of additional TCMs along the through route might help in further extending the speed reduction effect triggered by the gate. This is especially worthwhile to consider in thoroughfares with a residential function because vulnerable road users benefit even more from these speed reductions (R. Elvik, 2009, p. 50).

3.3 MEASURING THE IMPACT OF DIGITAL INFORMATION DISPLAYS ON SPEED: A DRIVING SIMULATOR STUDY

This chapter is based on:

Ariën, C.; Cornu, J.; Brijs, K.; Brijs, T.; Vanroelen, G.; Jongen, E.M.M.; Daniels, S.; Wets, G. (n.d.) Measuring the impact of digital information displays on speed: A driving simulator study. Submitted for first review in *Accident Analysis and Prevention*. [web of science: 5 year impact factor 2.699].

Proceedings:

Ariën, C.; Cornu, J.; Brijs, K.; Brijs, T.; Vanroelen, G.; Jongen, E.M.M.; Daniels, S.; Wets, G. (2014) *Measuring the impact of digital information displays on speed: A driving simulator study*. In: Proceedings of Transportation Research Board Annual Meeting, Washington, D.C. (USA), January 13-17, 2013.

Abstract

Speeding is a major problem in today’s society and is estimated to contribute to about 30 percent of all fatal crashes. The primary objective of this study was to examine the impact of digital information displays (DID) on speeding behavior at 70kph-to-50kph transition zones. Two real world locations with a high percentage of speeding violations are rebuilt as realistically as possible in a driving simulator. Sixty-six participants completed an 18.9km trip during which they passed four conditions (baseline with no display, Smiley, “You are speeding! / Thank you” or “Speed enforcement”) in a randomized order at one of the two locations. The first two messages are respectively a social approval/disapproval logo and a social approval/disapproval text message, while the “Speed enforcement” text message confronts drivers with the (financial) risk of receiving a fine (i.e., a message more explicitly related to enforcement).

Results show a significant speed reduction effect of the three digital messages compared to the baseline at one location, while at the other location only the “Speed enforcement” message induced a significant speed reduction. Overall, the speed reductions ranged from 1.9 to 3.2 kph with a maximum distance between 25 m before and 175 m after the DID. Overall, the “Speed enforcement” condition was found to be most effective (in terms of effect size as well as in terms of distance) in reducing speed. This result was confirmed by the post-experiment survey where messages indicating a speed enforcement or a fine were considered by the participants as most effective.

Finally, 500 meters after the DID only very limited speed differences (both in size and distance) were observed between the four conditions. These results imply that a message more explicitly related to enforcement is more effective in reducing speed in speed transition zones compared to messages that socially disapprove speeding.

Highlights

- Three digital information display messages were compared in a driving simulator
- “Speed enforcement” message induced the largest speed reduction up to 3.2 kph
- Smiley and “Too fast” messages also reduce speed compared to baseline
- Local speed reduction effect between 25 m before and 175 m after digital display
- Message related to speed enforcement or fine was considered most effective

3.3.1 Introduction

Speeding is a major problem in today's society (BIVV, 2011; OECD & ECMT, 2006; Safetynet, 2009b). Depending on the road type, 30 to 90 percent exceeds the posted speed limit (BIVV, 2011). Several studies have revealed that approximately 30 percent of all fatal accidents can be attributed to speeding (NHTSA's National Center for Statistics and Analysis, 2004; Safetynet, 2009b). Explanations for speeding behavior can be found within three (interactional) domains: the driver, the traffic environment and the vehicle (SWOV, 2012a). Demographic characteristics, personality traits, external influences, attitudes and habits are related to the driver (De Pelsmacker & Janssens, 2007; Safetynet, 2009b). Road design and situational traffic conditions are important issues within the domain of traffic environment (Martens et al., 1997). Finally, the current generation of vehicles (high maximum speed, comfort and power/weight ratio) makes it possible to achieve high speeds (Horswill & Coster, 2002). Some drivers report feeling more comfortable when they drive at relatively high speeds, especially when they are rarely (or never) confronted with the negative outcomes of speeding behavior (Harrison, Fitzgerald, Pronk, & Fildes, 1998).

Speeding is a problem especially at 70kph-to-50kph transition zones (BIVV, 2011; Dixon et al., 2008). Dixon et al. (2008) state that well defined transitional speed zones are necessary to encourage drivers to slow down gradually when they drive from, for example, a higher speed rural road to a lower speed urban road. Roadway features and roadside conditions must help drivers to adjust their driving speed according to the road environment. In addition to others, Hallmark et al. (2007), Dixon et al. (2008) and the Federal Highway Administration (2009a) describe a variety of traffic calming treatments which can reduce the driving speed in rural/urban transition zones. Horizontal and vertical displacements, pavement markings, landscape treatments and digital information displays all have the potential to reduce driving speed. In the sections below, we will focus on digital information displays.

A. Effectiveness of digital information displays

A digital information display (DID) is a radar activated sign that dynamically depicts oncoming vehicle speeds and/or messages on a large digital display (Fontaine & Carlson, 2001; Hallmark et al., 2007). Studies conclude that these devices have a positive effect in reducing the driving speed and that they are especially effective in case of speeding drivers (Rose & Ullman, 2003; Santiago-Chaparro et al., 2012; Ullman & Rose, 2005). DIDs can thus be used at problem locations (school zones, dangerous intersections, hazardous curves, work zones etc.) as part of a speed-control program (Rose & Ullman, 2003; Ullman & Rose, 2005).

Studies have found overall speed reductions of 2.3 kph up to 16.1 kph when a DID was installed (Bloch, 1998; Fontaine & Carlson, 2001; Mattox et al., 2007; Walter & Broughton, 2011). This speed reduction would lead to a significant decrease of injury collisions (6-9%) and fatal collisions (18%) at sites where a DID was operational. However, no lasting effect is observed once a DID is removed (Bloch, 1998; Walter & Broughton, 2011).

DIDs can also be very useful within freeway working zones. In one study, in situations where there was no treatment, the observed speed reduction was only 4 percent (Bowie, 2003). The installation of a DID led to a further speed decrease of 6 percent. Police presence was most effective with a total reduction of 20 percent (Bowie, 2003). Galizio et al. (1979) concluded that speed reductions reflect an overreaction effect to the threat of punishment when a marked police vehicle was present. This suggests that driving speed is controlled more by external threat than by the value of safe driving.

In school zones, DIDs also tend to be effective in reducing driving speed (Ullman & Rose, 2005). At DID locations in school zones, the average speed was reduced by about 8.2 kph in a study by Lee and colleagues (2006). Casey and Lund (1987) found that a DID was capable to reduce the proportion of vehicles exceeding the speed limit by at least 16 kph from 15 to 2 percent. However, this effect was only achieved during the time the DID was actually in use. They also suggest that combined police enforcement is a crucial factor in DID effectiveness.

Although DIDs have tended to be effective in reducing speed, this effect was only found in the direct vicinity of the DID (i.e., no distance halo effect). In their field experiment, Walter and Broughton (2011) found that the speed reduction effect was limited to 400 m after the display. Furthermore, Santiago-Chaparro et al (2012) found that drivers started to increase their speed 90-150 m after the speed feedback sign. This is similar to automated speed cameras where drivers sometimes reduce their speed when approaching the camera and then accelerate as soon as they have passed by (Franz & Chang, 2011).

B. Messages on digital information displays

Although the appearance of the message (i.e., static or flashing, color scheme etc.) is important (Castro & Horberry, 2004; Federal Highway Administration, 2003, 2012; Yang, Waters, Cabrera, Wang, & Collyer, 2005), this study focuses more on the content of the message.

According to Van Houten et al. (1980), posted feedback of speeding information is effective because of two reasons. First, it introduces a social assessment factor (approval/disapproval) and second it is possible that the given feedback concerning speeding implies police surveillance (deterrence). Subjective norms (i.e., beliefs about whether a specific behavior will be reinforced or punished by others) play a key role in the approval/disapproval mechanism because drivers possibly will slow down as they believe that speeding is not appreciated by others (Parker, Manstead, Stradling, Reason, & Baxter, 1992; Van Houten et al., 1980). The deterrence mechanism is also often used to achieve behavioral change: the behavior of an individual can be modified by inducing fear for the consequences of committing an illegal act (in this case: a traffic/speeding violation) (Gibbs, 1975; Homel & Wilson, 1988; OECD & ECMT, 2006). Deterrence is a concept where people react through fear for possible punishment in the short term. Here, the deterring effect of a threat is higher when perceived certainty, severity and/or immediacy of punishment increase. In the long term, deterrence refers to the formation of habits and moral education which are based on the short term threats over time (H. L. Ross, 1982). Furthermore, the perceived (subjective) and actual (objective) risk of detection are two risk functions within a driver. The subjective risk is the result of the road user's perception of the intensity of enforcement and the objective risk reflects the actual level of enforcement (OECD & ECMT, 2006; Riley, 1991; Zaal, 1994). According to Riley (1991), an optimal situation is achieved when the subjective risk equals (or exceeds) the objective risk.

A study conducted at work zones in Virginia (Rose & Ullman, 2003) suggested that the following warning messages had a positive impact on high-speed drivers: "Excessive speed / Slow down", "High speed / Slow down", "Reduce speed / In work zone" and "You are speeding / Slow down". These messages were only displayed when a driver was speeding and they all generated significant speed reductions. Aforementioned messages are sometimes preferred over numerically represented speed because they tell the driver what action he or she should undertake (it is a strong command). Especially the last message is directly oriented to the speeders (Rose & Ullman, 2003).

Wrapson et al. (2006) performed a study in a 50 kph zone to measure the effect of a DID that consecutively depicted one of the following three messages:

- The average speed at the site: motorists may reduce their speed in order to comply with the behavior of the other road users
- A warning that the drivers' speed was being measured: drivers may reduce their speed in order to avoid possible fines
- A combination of both messages

These three messages had a positive impact on the observed driving speed. This suggests that both social comparison and the potential presence of police enforcement are mechanisms by means of which driver speed may be reduced (Van Geirt, 2006; Wrapson et al., 2006).

The current study aims to investigate different types of DID messages which are related to the approval/disapproval versus deterrence strategy: two messages are based on the approval/disapproval mechanism, while a third message makes a more explicit link to the presence of police control and thus, is related more to fear for punishment as a result of speeding.

3.3.2 Objectives

Since speeding is a problem in 70kph-to-50kph transition zones, the primary objective of this study is to examine the effectiveness of three DID messages on speed (BIVV, 2011; Dixon et al., 2008).

Message 1 and 2 are more based on the social approval/disapproval mechanism, while message 3 can be categorized as a deterrence message and is more explicitly related to police enforcement and thus meant to induce fear for a speeding fine.

Message 1: a DID with a laughing smiley when the driver's speed is below the speed limit (50 kph); otherwise a sad smiley.

Message 2: a DID with the text "You are speeding!" when the driver is exceeding the speed limit; otherwise "Thank you". Hereafter, this condition will be referred as "Too fast".

Message 3: a DID with a warning sign "Speed enforcement". This message is always displayed, thus independent of the current driver's speed.

Figure 38 DID messages

Two real world locations with a high percentage of speeding violations and a comparable cross-sectional profile were selected from a registered police database. These locations were rebuilt in the driving simulator at Hasselt University's Transportation Research Institute. At each location, the three types of DID messages and one baseline section (i.e., no implementation of a DID) were examined. We addressed the following research questions:

a. Does the presence of a DID (vs. baseline condition) have an effect on mean speed and mean acceleration/deceleration?
b. Is there a difference in effectiveness between the digital messages?
c. How far does the effect of a DID extend in terms of distance along the road (i.e., distance halo effect)?
d. Concerning the distance halo effect, is there a difference between the digital messages?

3.3.3 Methodology

A. Participants

Eighty volunteers (all gave informed consent) participated in the study. Ten did not finish the experiment due to simulator sickness and four encountered a technical problem. No outliers were identified based on the three interquartile distance criteria. Thus, 66 participants (41 men), approximately equally divided over four age categories from 20 to 75 years old (mean age 45.2; SD age 17.0) remained in the sample. All participants had at least two years of driving experience. Age and gender were not taken into account as between-subject factors in the statistical analyses because the sample size per age and gender category was too limited.

B. Driving simulator

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-based (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual/auditory (e.g. sound of traffic in the environment and of the participant's car) feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images. Three projectors offer a resolution of 1024 × 768 pixels and a 60 Hz frame rate. The data, which was collected at a 60 Hz frame rate, was interpolated to a 1 m distance interval before starting the data analysis.

C. Scenario

Road segment selection and description

The objective was to select two roads with similar percentages of speeding violations, comparable cross-sectional profiles and similar road surrounding environments. This selection was based on a data-driven approach and used the following variables: percentage of speed violations (i.e., the number of speed violations divided by the number of controlled vehicles), speed limit, number of lanes, number of curves and intersections, priority type, and presence of a median, cycle lanes, footpath, zebra crossings, parking lane and buildings. The speeding violations and speed limit data were extracted from an official police database and all the environmental variables were investigated through satellite images from Google Earth. The roads were first classified by their speeding violation rate, because roads with a high percentage are more problematic than roads with a low speeding percentage. To make a final decision, the most interesting (and comparable) locations were visited.

The two selected roads, with a violation rate of 22.5% and 18.8% respectively, each contain a 70kph-to-50kph speed transition with 2x1 lanes, an adjacent cycling lane and a roundabout in the 50 kph speed zone. At each location, three types of digital messages are implemented in the driving simulator. More detailed information about the selected locations can be found below and in Figure 39.

Road segment development

To rebuild the selected locations in the driving simulator environment, a procedure called geo-specific database modeling (Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008b) was adopted. This procedure consists of replicating a real-world driving environment in a simulated virtual environment and is to be differentiated from simulator research where often the driving scenarios are fictional. In order to reproduce the existing situations as realistic and detailed as possible, we made use of photographs, videos, detailed field measurements, AutoCAD drawings, and Google Street View. Pictures of the two real world 50 kph environments and their simulated replica can be found in Figure 39.

Figure 39 Real world vs. simulator images at location A (top) and at location B (bottom)

Scenario design

The overall scenario is a systematic combination of the real life replicated sections (location A or B) with a set of 2km long filler pieces, differing from the analysis sections with respect to design, speed limit and surrounding environment and meant to provide some variation while driving. Figure 40 includes an overview of the scenario of the two selected locations with the corresponding speed limits.

Both analysis locations contain a transition from a rural to an urban environment and have a length of 3,100 m. The DID is located at 170 m (location A) or 575 m (location B) after the 70kph-to-50kph transition and had a size of 150 x 120 cm. The DID is set at the relative distance of 0 m (cf. Figure 40). Since we are also interested in the distance halo effect of the DIDs, we included a replica of the real-world roundabouts and a 500 m long road segment with a speed limit of 50 kph in the scenario. The roundabouts are located at respectively 450 m (location A) and 370 m (location B) after the DID. The sample is divided into two groups: one group will drive at location A and the other group will pass at location B. All participants are exposed to the four conditions: one baseline condition (no DID was implemented) and three DID messages.

Weather conditions were sunny and dry and random traffic was generated in the opposite direction. There was no traffic present in front of or following the driver in the participant's driving lane.

Procedure and design

Participants were asked for their voluntary cooperation and requested to fill out a form with some personal data (e.g. date of birth, driving experience, gender). After a general introduction, drivers acquainted themselves with the driving simulator by handling various traffic situations (e.g. urban and rural areas, highway, curves, roundabout, traffic lights) during two practice trips of 3 and 7km respectively. Then they completed the experimental trip of 18.9km at one of the two locations, group A (n = 32) drove at location A and group B (n = 34) passed at location B. During this experimental trip, the drivers were confronted with all four conditions (no display, Smiley, "Too fast", "Speed enforcement") in a randomized order. Subjects were asked to drive as they normally would in their own car and to apply the traffic laws as they would (or would not) do in reality. A GPS voice instructed them during the trip to follow the main road and go straight on at the roundabouts.

After the experimental session, participants were asked to fill out a questionnaire. In this survey participants were asked to score twenty different messages which could be displayed by a DID. The messages were presented during 2 seconds on a large screen. The exact question was: "To what extent do you think speeders will adapt their behavior when the following messages are displayed in real life on a digital panel?". Subjects could mark points on a scale from 1 (not at all) to 10 (completely) with an interval of 0.25.

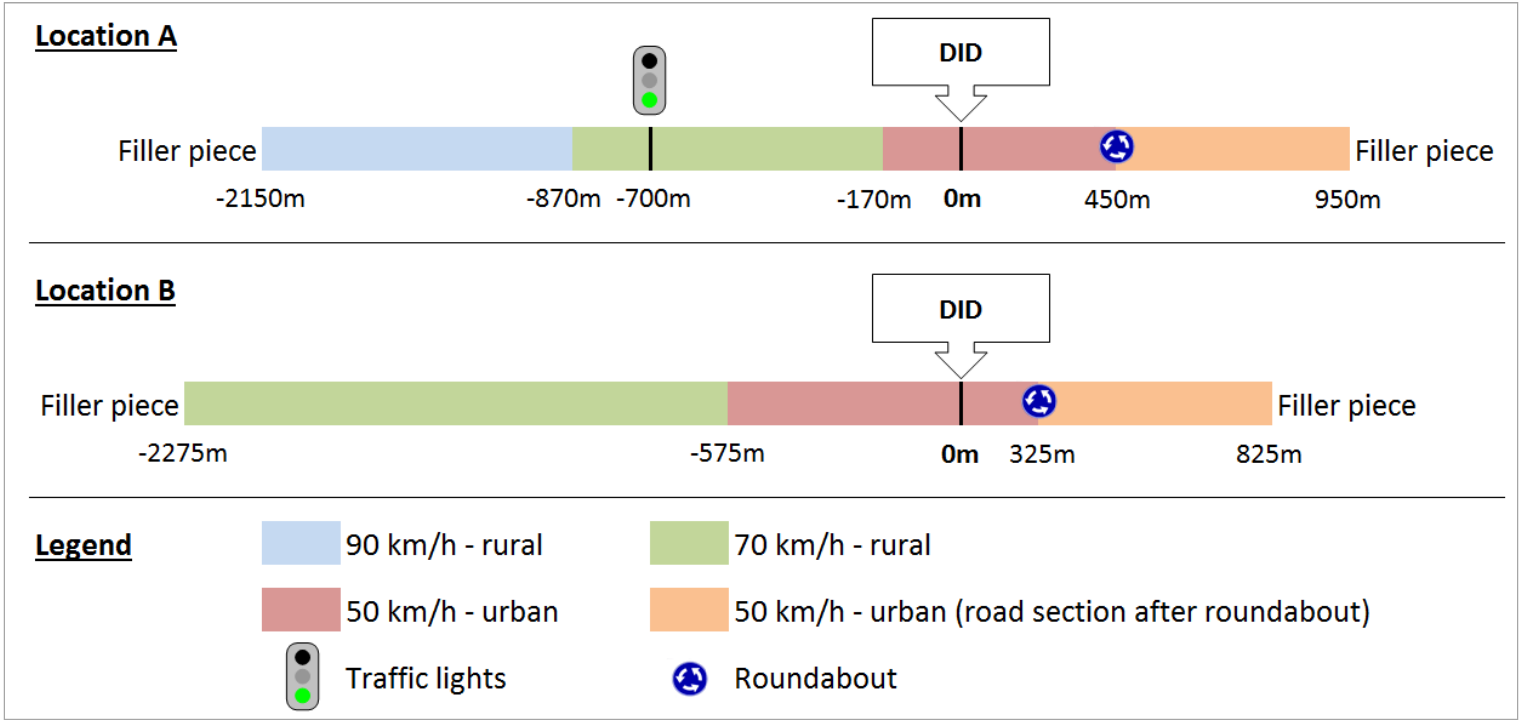


Figure 40 Scenario overview

D. Data collection and analysis

Dependent measures

Driving performance measures for both longitudinal and lateral control were recorded by the simulator. For this study, measures for longitudinal control were of particular interest. Mean speed [kph] is selected because it is used as an indicator for safe driving (Safetynet, 2009b). Mean acceleration/deceleration (acc/dec) [m/s^2] is interesting because fluctuations in acc/dec indicate (large) changes in speed and can cause discomfort. Sometimes it is difficult for drivers to anticipate safely these fluctuations, thereby increasing the chance for rear-end collisions (Dewar & Olson, 2007).

Data analysis

Data analysis for mean speed and mean acc/dec is based on a number of measurement zones along the driving scenario. First, one random zone of 500 m was analyzed (starting 1750 m before the DID) to see whether significant differences exist between the four conditions. Under normal circumstances, no significant differences would occur because the DID do not have an influence at this distance. A randomized within (condition: no display or one of the three digital messages: Smiley, "Too fast" or "Speed enforcement") subjects repeated measures multivariate analysis of variance (MANOVA) was conducted on the two speed parameters for each location separately.

Since this study focuses on speed-related behavior (cf. research questions a and b) nearby the DID, six zones before and ten zones after the displays were analyzed. Each zone has a length of 25 m, resulting in an analysis section of 400 m (from -150 m until 250 m on Figure 41). Therefore, a 4 (condition) x 16 (zones of 25 m) within subjects repeated measures MANOVA for location A and location B was conducted for the two speed parameters.

To examine how far any effect of the DID endured in distance (cf. research question c), nine zones of 50 m after the roundabout (see Figure 40; 450 m after the DID at location A; 325 m after the DID at location B) were analyzed. Therefore, a 4 (condition) x 9 (zones of 50 m) within subjects repeated measures MANOVA was conducted on the two speed parameters for the two locations separately.

Finally, a within subjects ANOVA was conducted to examine whether the scores of the 20 different DID messages in post-experiment survey were significantly different.

For all analyses, additional post-hoc univariate tests and ANOVA's were conducted and p-value was set at 0.05 to determine statistical significance. For MANOVA's

F- and probability values (Wilks' Lambda) are reported. For univariate tests and ANOVA's, corrected F- and probability values (Greenhouse-Geisser) are described.

3.3.4 Results

A. Control zone

The purpose of the control zone was to see whether there are significant differences between the conditions on a road section where the DID had no influence (i.e., 1750 m before the DID). The MANOVAs for each location separately revealed no significant effect of the factor Condition (location A: $F_{(6,84)} < 1$, p = 0.422, η_p^2 = 0.031; location B: $F_{(6,196)} < 1$, p = 0.510, η_p^2 = 0.026). As was expected, no significant differences were found between the four display conditions in this control zone.

B. Immediate vicinity of digital information displays

Table 12 presents the multivariate and univariate statistics for the dependent measures for sixteen 25 m zones (between 150 m before and 250 m after the DID), separately for the two locations.

The MANOVAs for the two locations showed significant effects of the factors Condition, Zone and Condition x Zone. Subsequent univariate statistics revealed that Condition x Zone was significant for mean speed and marginally significant for mean acc/dec. These two-way interaction effects were further analyzed and are described below.

Table 12 Multivariate and univariate statistics for mean speed and mean acceleration/deceleration

	Location A		**Location B**	
Variable	*F (dfs)*	*p*	*F (dfs)*	*p*
MANOVA				
Condition	2.3 (6, 184)	**0.034**	2.9 (6, 196)	**0.011**
Zone	2.8 (30, 928)	**<.0005**	36.8 (30, 988)	**<.0005**
Condition x Zone	2.0 (90, 2788)	**<0005**	2.3 (90, 2968)	**<.0005**
Univariate statistics				
Mean speed				
Condition	3.9 (3, 82)	**0.015**	4.0 (3, 91)	**0.013**
Zone	2.3 (2, 56)	0.116	80.4 (2, 76)	**<.0005**
Condition x Zone	2.5 (7, 214)	**0.021**	3.0 (9, 282)	**0.002**
Mean acc/dec				
Condition	1.0 (3, 79)	0.387	1.8 (3, 87)	0.160
Zone	3.5 (4, 139)	**0.007**	31.1 (4, 135)	**<.0005**
Condition x Zone	1.7 (12, 360)	*0.068*	1.6 (13, 416)	*0.073*

p ≤ 0.05; *p ≤ 0.1*

Mean speed

Figure 41 (left panel) clearly shows that at **location A** the lowest mean speeds were measured in the "Speed enforcement" condition. The pairwise comparisons showed no significant speed difference between the four conditions between -150 m and -25 m. Mean speed started to decrease from 25 m before the DID in the "Speed enforcement" message compared to the other three conditions. The "Speed enforcement" message generated a significantly lower mean speed compared to:

- the baseline between -25 m and 175 m. Mean speed differences ranged from 2.0 to 3.2 kph.
- the Smiley between 25 m and 100 m. Mean speed differences were between 2.1 and 2.2 kph.
- the "Too fast" message between 0 m and 75 m. Mean speed differences ranged from 1.9 to 2.0 kph.

There were no significant differences in mean speed between the baseline, the Smiley and the "Too fast" message. Finally, the differences in mean speed disappeared further along the road.

Similar analyses were performed for **location B**. The results are illustrated in Figure 41 (right panel). Although mean speeds were equal between -150 m and -50 m, mean speed started to decrease from 50 m before the DID in the Smiley condition and from -25 m in the "Too fast" and "Speed enforcement" condition compared to the baseline. The significant speed reduction effect of the last two conditions sustained until 100 m after the DID. The mean speed difference between the baseline and "Too fast" message ranged from 2.3 kph to 3.1 kph. The difference with the "Speed enforcement" message was comparable and reached 3.2 kph at its maximum. The effect of the Smiley was detected 25 m earlier (at -50 m), but this effect disappeared at 75 m after the DID. The effect on speed was between 1.9 kph and 2.8 kph. There was no significant mean speed difference between the three DID conditions. Between 100 m and 250 m there were no longer significant speed differences among the four conditions. The roundabout which is located at 350 m after the DID in location B, has a speed reduction effect which is clearly illustrated in Figure 41 (right panel).

To summarize, we found a significant speed reduction effect of the "Speed enforcement" messages compared to the baseline condition from 25 m before the DID until 175 m after the DID at location A and until 100 m at location B. The Smiley and "Too fast" message only generated a positive effect on mean speed compared to the baseline at location B. The largest mean deceleration was located in the direct vicinity of the DID, i.e., from 25 m before until 25 m after the DID. Overall, the "Speed enforcement" message was found to be most effective, both in terms of speed reduction size as in terms of distance.

Mean acceleration/deceleration

Although Figure 42 (left panel) shows a slight deceleration between 50 and 25 m before the DID in the three test conditions with a DID message, the post-hoc analysis for the marginally significant interaction of Condition x Zone showed no significant differences in mean acc/dec between the four conditions at **location A**. Furthermore, mean acc/dec was rather constant in the different analysis zones.

Figure 42 (right panel) shows a dip in mean acc/dec just before the DID compared to the baseline for **location B**. This difference was significant for the three DID messages between 50 m and 25 m before the DID ($F_{(2,68)} = 4.3$, $p = 0.016$). During the last 25 m before the DID, mean deceleration was significantly larger in the "Too fact" and "Speed enforcement" conditions compared to the baseline. Furthermore, the mean deceleration with the "Speed enforcement" message was also larger than the Smiley. There were no other significant differences in mean acc/dec between the four conditions in other zones. The increasing mean deceleration further along the road in location B can be related to the presence of the roundabout at 350 m after the DID where drivers had to lower their speed.

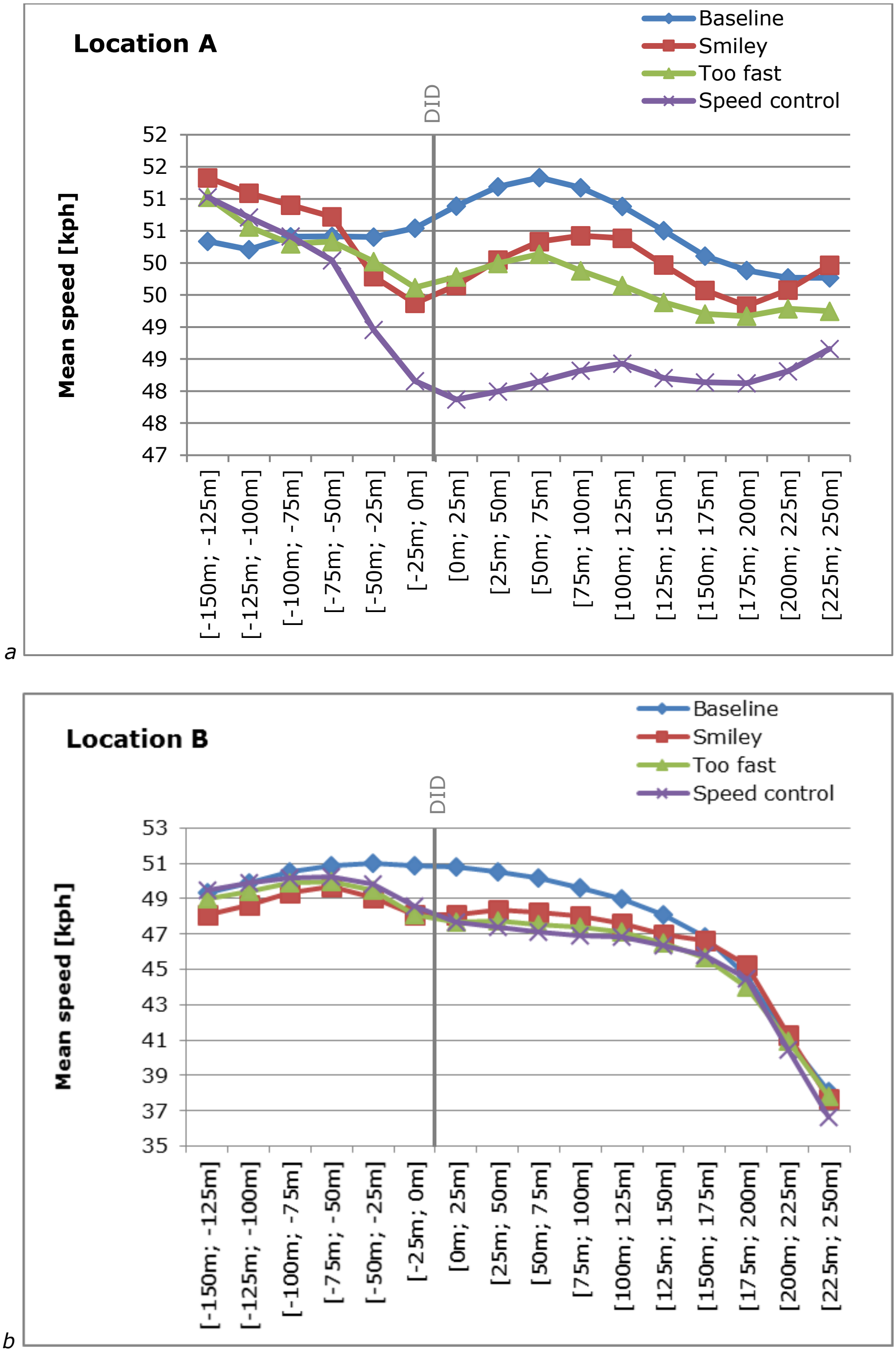
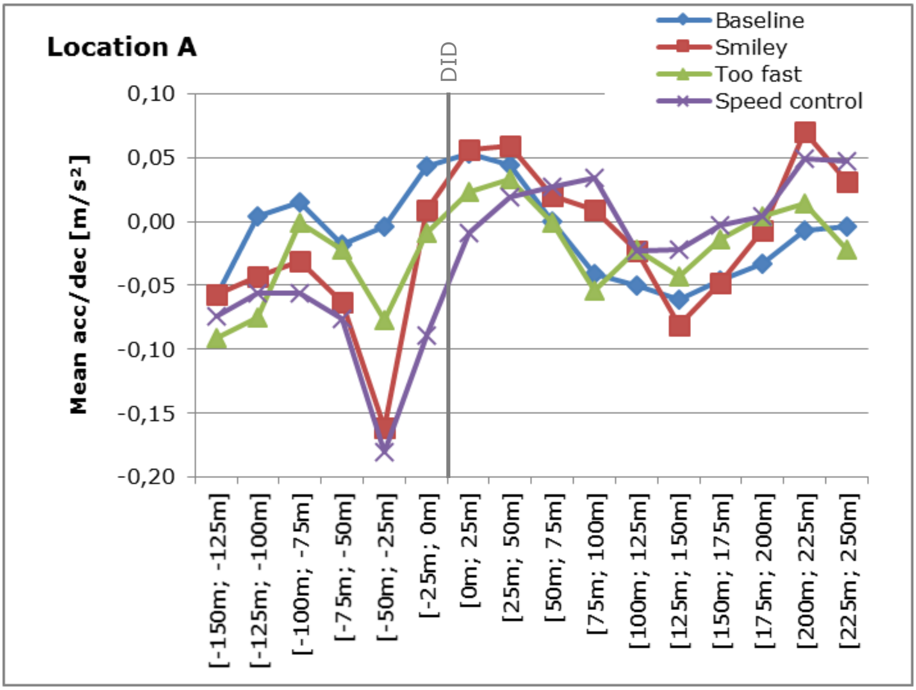
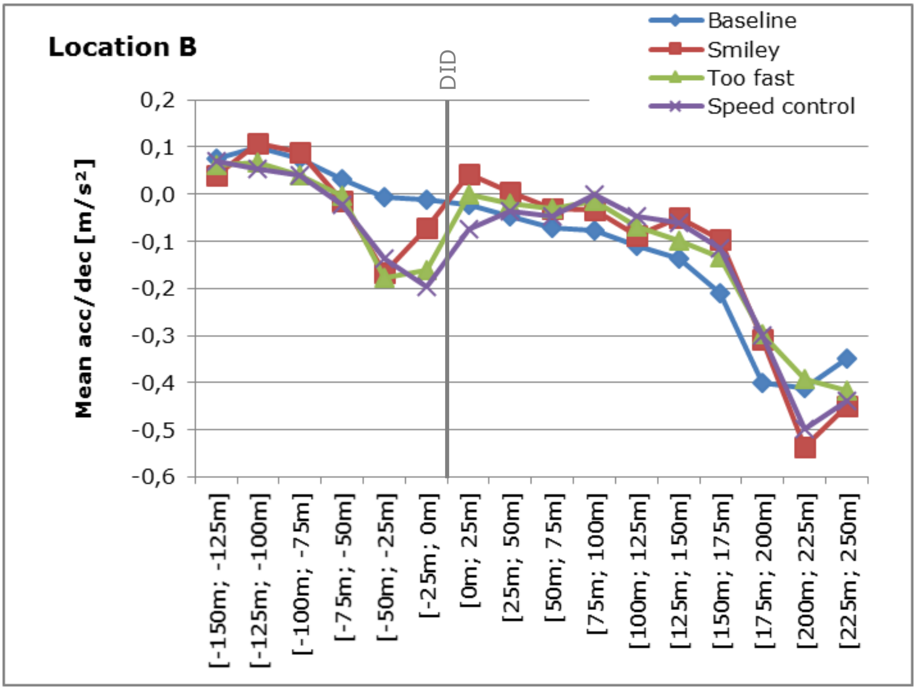


Figure 41 Mean speed in the immediate vicinity of DID at (a) location A and (b) location B



a



b

Figure 42 Mean acc/dec in the immediate vicinity of DID at (a) location A and (b) location B

C. Distance halo effect

To study the effect of a DID over a somewhat longer distance (cf. research question c), nine consecutive zones of 50 m after the roundabouts were considered. At location A the roundabout was located at 450 m downstream the DID, whereas at location B the roundabout was located at 325 m after the DID. Due to this difference, both locations were analyzed separately. Both MANOVAs (see Table 13) revealed no significant main effect for the factor Condition. However, the factor Zone and the interaction Condition x Zone were significant at both locations. Subsequent univariate statistics revealed that Condition x Zone was significant for mean speed at location A and marginally significant at location B. Only the main effect of Zone was significant for mean acc/dec. The post-hoc tests are described below.

Table 13 Multivariate and univariate statistics for mean speed and mean acceleration/deceleration

	Location A		Location B	
Variable	*F (dfs)*	*p*	*F (dfs)*	*p*
MANOVA				
Condition	1.5 (6, 184)	0.194	1.0 (6, 196)	0.401
Zone	160.1 (16, 494)	**<.0005**	172.4 (16, 526)	**<.0005**
Condition x Zone	1.5 (48, 1486)	**0.010**	1.5 (48, 1582)	**0.015**
Univariate statistics				
Mean speed				
Zone	484.8 (2, 72)	**<.0005**	594.7 (3, 100)	**<.0005**
Condition x Zone	2.2 (7, 219)	**0.037**	1.9 (6, 198)	*0.084*
Mean acc/dec				
Zone	68.6 (4, 136)	**<.0005**	60.9 (3, 112)	**<.0005**
Condition x Zone	<1 (10, 311)	0.525	1.1 (11, 354)	0.356

p ≤ 0.05; *p ≤ 0.1*

Mean speed

Subsequent univariate tests for mean speed at **location A** revealed a significant higher mean speed in the baseline condition compared to the Smiley between 200 m and 300 m after the roundabout and these ranged from 2.8 to 3.1 kph ([200-250 m]: p = 0.029; [250-300 m]: p = 0.036). The "Speed enforcement" message generated a speed reduction effect between 200 m and 250 m after the roundabout with the size of the reduction being 2.6 kph lower than speed in the baseline condition (p = 0.031). As can be seen in Figure 44 (left panel), mean speeds were comparable between the different conditions in the other zones. In addition, mean speed increased after the roundabout and stabilized close to the speed limit (50 kph) between 150 m and 200 m after the roundabout in the three DID conditions. In the baseline condition, mean speed increased even further until 250 m after the roundabout.

Post-hoc analysis for the marginally significant interaction of Condition x Zone at **location B** only showed a significantly higher mean speed between 350 m and 400 m after the roundabout for the Smiley compared to the "Too fast" message (p = 0.004). This was a speed difference of 1.8 kph. Furthermore, there were no significant differences in mean speed between the four conditions (see Figure 44 right panel). Similar to location A, mean speed increased after the roundabout and reached a mean speed close to the speed limit of 50 kph between 150 m and 200 m in the conditions with the "Too fast" and "Speed enforcement" messages. In the baseline and Smiley conditions, mean speed stabilized between 200 m and 250 m.

Mean acceleration/deceleration

The main effect of the factor Zone for mean acc/dec at **location A and B** showed a peak in mean acceleration of 0.6 m/s² between 50 m and 100 m after the roundabout. The results for mean acc/dec show that participants accelerated after leaving the roundabout (with a peak between 50 m and 100 m after the roundabout) and that acceleration decreased to approximately zero at 200-250 m after the roundabout, indicating that from thereon participants maintained a rather constant speed.

D. Survey results

The ANOVA revealed that the scores for the different messages were significant different ($F_{(8, 512)}$ = 27.6, p < .0005). Figure 43 shows the three messages with the highest scores. A message of speed enforcement in combination with a logo (cf. Figure 43a) tends to be the most effective (M = 8.03, SD = 0.17). This message was significantly different from all other messages (p ≤ 0.01), except from the messages in Figure 43b (p = 0.171) and Figure 43c (p = 0.152). Figure 43b shows a text message that warns drivers for a speed enforcement (M = 7.79, SD = 0.17) and is thus comparable to the "Speed enforcement" message in the driving simulator scenario. Figure 43c includes a message which communicates that a fine for speeding amounts to at least 50 euros (M = 7.72, SD = 0.22).

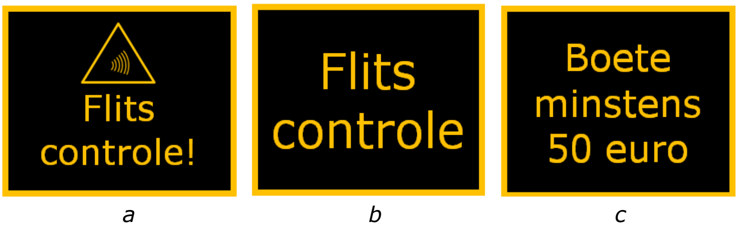
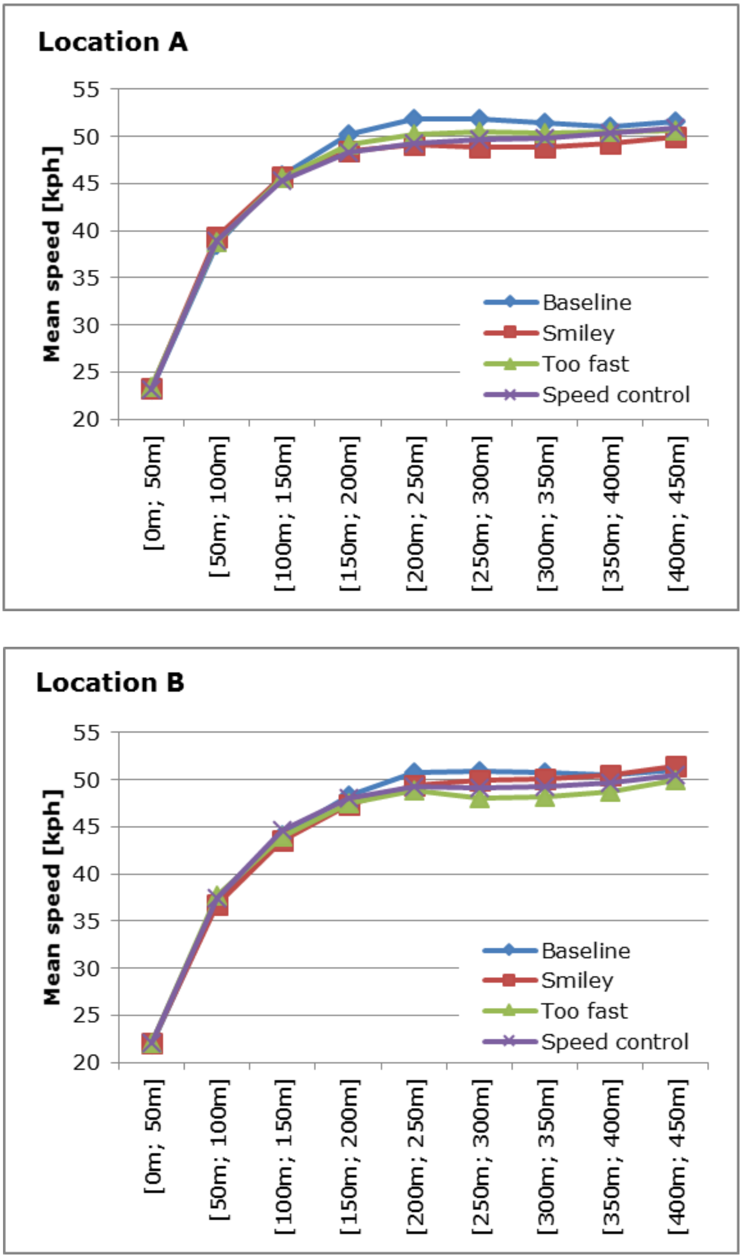


Figure 43 Digital display TOP-3 of the post-experiment survey (a) digital display with highest mean score "Speed enforcement + logo"; (b) digital display with second highest mean score "Speed enforcement"; (c) digital display with third highest score "Fine at least 50 euros"



a

b

Figure 44 Distance halo effect for mean speed at (a) location A and (b) location B

3.3.5 Discussion

In this study, two real-world road sections with a high percentage of speeding offences were selected and replicated in the driving simulator. Both locations had a comparable cross-sectional profile with a rural (70 kph) to urban (50 kph) road transition. At every location four conditions were implemented (i.e., no DID or one of the three digital messages: Smiley, “You are speeding! / Thank you” or “Speed enforcement”) and each group of participants was confronted with these four condition at one of the two locations.

A. DID-effects in the immediate vicinity of digital information displays

We found a significant speed reduction effect of the “Speed enforcement” message compared to the baseline condition, the Smiley and the “Too fast” message at location A. The difference in mean speed between the baseline and the “Speed enforcement” message was the largest (up to 3.2 kph) and lasted over the longest distance (from 25 m before until 175 m after the DID). The difference between the “Speed enforcement” message and the other two DID messages was smaller (between 1.9 and 2.2 kph) and lasted no longer than 75 m.

At location B on the other hand, a significant speed reduction effect was found for the three DID messages compared to the baseline. Again, the effect of the “Speed enforcement” message was the largest (up to 3.2 kph) and lasted over the longest distance (between -25 m and 100 m). The size of the effect is thus rather comparable with location A. However, as the roundabout at location B was located closer to the DID (350 m downstream), drivers started to decelerate in all conditions (also in the baseline) and therefore reached the same mean speed level in the four conditions earlier (at 100 m after the DID) compared to location A (175 m after the DID). Besides the “Speed enforcement” message, the “Too fast” condition also had a positive effect on mean speed (-2.3 to -3.1 kph) between -25 m and 100 m. Finally, the Smiley showed a speed reduction effect of 1.9 to 2.8 kph between 50 m before until 75 m after the DID. Interestingly, there were no significant mutual differences found between the three DID messages at location B. Therefore, we can conclude that the established speed reduction can be attributed to the mere presence of the device itself. Based on Elvik’s Power Model (R. Elvik, 2009, p. 58), speed reductions between 1.9 and 3.2 kph could result in a decrease of 7.4 to 15.4% for fatal accidents and 2.9 to 6.2% for injury accidents.

The speed reductions (ranging from 1.9 to 3.2 kph) are comparable to those obtained in other (field) experiments where a DID was implemented. Other studies found reductions of 8.2 kph (Choulki Lee et al., 2006), 5.3 kph (Mattox et al., 2007), 6% (i.e., 3kph when the average speed is equal to 50 kph) (Bowie, 2003), 2.24 kph (Walter & Broughton, 2011) and 0.8 kph (A. H. Jamson & Merat,

2007) after installation of a DID. Studies on other traffic calming measures (e.g. transverse rumble strips) found comparable average speed reductions of 3.2 kph (Fontaine & Carlson, 2001) and 5.9 kph (Ariën et al., 2016; Godley, 1999; Montella et al., 2010). Finally, the survey results support the findings obtained in the driving simulator experiment: the message indicating a speed enforcement or a fine was most effective.

The fact that the "Speed enforcement" message is more effective in reducing speed compared to the Smiley and the "Too fast" messages can possibly be explained in terms of the underlying message strategies: i.e., deterrence versus approval/disapproval. Galizio et al. (1979) for instance, state that driving speed is controlled more by external threat (of receiving a fine) than by the value of safe driving. Maybe, a Smiley through its rather suggestive and symbolic character is too 'soft' as an approach to stimulate drivers to lower their speed. Interestingly, Van Houten et al. (1980) concluded that posted speed-related feedback is effective because drivers think that this feedback implies police surveillance. With respect to the latter, several studies (Bloch, 1998; Casey & Lund, 1993) found that DIDs in combination with police enforcement are a crucial factor to increase efficacy. To summarize, the results for this study bring us to the conclusion that fear for a speeding fine is a more effective message strategy for reducing speed compared to the approval/disapproval message strategy.

With respect to mean acc/dec, the strongest deceleration maneuver was established in the last 50 m before the DID. The deceleration rate around the DID in this study is not higher than -0.20 m/s² (cf. Figure 42). This can be seen as a safe and still comfortable deceleration in light of values recommended by other studies: -0.85 m/s² (PIARC, 2003), -3.40 m/s² (PIARC, 2003) or -4.40 m/s² (Hu & Donnell, 2010). These results are relevant and positive for the avoidance of rear-end collisions and (sudden) disturbances in traffic flow.

B. Distance halo effects

To see how long the speed reduction effect of the DID was maintained in terms of distance (cf. research question c), nine zones of 50 m following the roundabout (i.e., 450 m after the DID at location A and 325 m at location B) were analyzed. The results showed only limited differences in mean speed between the different conditions. At location A, the Smiley and "Speed enforcement" message generated lower speeds (between 2.6 and 3.1 kph) compared to the baseline. The "Too fast" message revealed lower a speed (1.8 kph) compared to the Smiley. We can conclude that the effect of digital messages is rather a local phenomenon.

This finding is in line with results from field experiments conducted by Santiago-Chapparro et al. (2012) and Walter and Broughton (2011) who found that the speed reduction effect of speed indicator devices was limited to respectively about 90-150 m and 400 m after the speed feedback sign. Another conclusion was that no lasting effect was observed once the speed indicator device was removed (Casey & Lund, 1993; Walter & Broughton, 2011). This local speed reduction effect has also been found in other studies concerning speed cameras (Medina, Benekohal, Hajbabaie, Wang, & Chitturi, 2009; SWOV, 2011a). Furthermore, Ariën et al. (2013a) (paragraph 3.1) concluded that traffic calming measures (in this case: gate constructions) only reduced speed locally.

3.3.6 Limitation and future research

In case of driving simulation, external validity often is raised as a methodological issue. Although the motivation as well as the experience of rewards and punishments of participants is hard to manage in a driving simulator (Ranney, 2011), Lee and Abel-Aty (2008) have indicated that DIDs can be examined in a driving simulator experiment. Furthermore, Bella (2008) and Godley et al. (2002) concluded that speed parameter-related values obtained by driving simulation reach relative validity when compared to results obtained with field observation techniques. The geo-specific database modeling technique also increases reliability and validation of the experiment and the results (Yan et al., 2008b). In addition, the simulator used in this study is equipped with a 180° field of view, which satisfies the prescribed minimum of 120° field of view for the correct estimation of longitudinal speed (Kemeny & Panerai, 2003).

Future research on DIDs could best be focusing on potential haloing effects and/or determination of the optimal location. Probably, different effects will be found on other road types or roads with a different speed regime. In this study, the presence of a roundabout following the DID might have impacted the DID-effect. Finally, additional personal characteristics can have an influence on drivers' speed choice.

3.3.7 Conclusion and policy recommendations

Considering the results for mean speed, DIDs can be considered as an interesting speed reduction measure. The results show that the message "Speed enforcement" was most effective in reducing the driving speed, followed by "Too fast" and the Smiley. This implies that confronting drivers with the (financial) risk of receiving a fine is more effective in reducing speed compared to the social approval/disapproval messages. Additional support comes from the survey which showed that messages indicating a speed enforcement or a fine were considered as most effective. Police departments may use these results to invest in more effective digital information displays for speed reduction. An important constraint however, is that results show that this speed reduction effect is difficult to sustain.

Considering the results of this study, the DID with the message "Speed enforcement" can be recommended at locations with an important residential function that also have a speeding problem (e.g. school zones). The combination of a DID with other speed reduction measures would also be expected to increase its effectiveness. However, for maintaining the speed reduction effect and the credibility of these displays, police controls should be performed in the immediate vicinity and at regular intervals.

Chapter 4

EMPIRICAL STUDIES CONCERNING TANGENT-TO-CURVE DISCONTINUITIES

4.1 THE EFFECT OF PAVEMENT MARKINGS ON DRIVING BEHAVIOR IN CURVES: A SIMULATOR STUDY

This chapter is based on:

Ariën, C.; Brijs, K.; Vanroelen, G.; Ceulemans, W.; Jongen, E.M.M.; Daniels, S.; Brijs, T.; Wets, G. (2016) The effect of pavement markings on driving behavior in curves: a simulator study. In *Ergonomics*, doi: 10.1080/00140139.2016.1200749. [web of science: 5 year impact factor 1.804]

Proceedings:

Ariën, C.; Brijs, K.; Ceulemans, W.; Vanroelen, G.; Jongen, E.M.M.; Daniels, S.; Brijs, T.; Wets, G. (2012). *The effect of pavement markings on driving behavior in curves: a simulator study.* In: Proceedings of Transportation Research Board Annual Meeting, Washington, D.C. (USA), January 22-26, 2012.

Abstract

This study investigates the effect of two pavement markings (transverse rumble strips (TRS) and a backward pointing herringbone pattern (HP)) on speed and lateral control in and nearby curves. Two real-world curves with strong indications of a safety problem were replicated as realistic as possible in the simulator.

Results show that both speed and lateral control differ between the curves. These behavioral differences are probably due to curve-related dissimilarities with respect to geometric alignment, cross-sectional design and speed limit. TRS and HP both influenced mean speed and mean acceleration/deceleration but not lateral control. TRS generated an earlier and more stable speed reduction than HP which induced significant speed reductions along the curve. The TRS gives drivers more time to generate the right expectations about the upcoming curve. When accidents occur primarily near the curve entry, TRS is recommended because this measure reduces speed before entering the curve. The HP has the potential to reduce accidents at the curve end because it keeps driving speed at a lower level along the curve.

Highlights

- Driving simulator study on the effect of pavement markings near dangerous curves
- Transversal rumble strips (TRS) generate an earlier and more stable speed reduction
- Herringbone pattern (HP) induce significant speed reductions along the curve
- TRS give drivers more time to generate right expectations about the upcoming curve
- TRS and HP did not influence lateral control

4.1.1 Introduction

Curves typically go together with an increased safety risk: accident rates are 1.5 to 4 times higher than in tangents (i.e., straight road sections) and 25 to 30% of all fatal accidents occur in curves. Single-vehicle run-of-road accidents represent approximately 60 to 70% of all fatal curve-related accidents, whereas head-on collisions occur in 11% of the fatal crashes (Safetynet, 2009a; Srinivasa et al., 2009).

Charlton (2007) proposed three main causative factors for accidents in curves, i.e., inappropriate speed monitoring, failure to maintain proper lateral position, and inability to meet increased attentional demands. Milleville-Pennel, Jean-Michel and Elise (2007) describe that 72% of the accidents in curves have "excessive speed and/or steering wheel errors" as major contributing factor.

Extensive experimental research on human factors and road design determined that these behavioral problems often relate to the geometric properties of curves (Brenac, 1996; R. Elvik et al., 2009; Khan et al., 2013; Safetynet, 2009a). Among curve design aspects most frequently mentioned as having detrimental effects on road safety are low curve radii, inappropriate superelevation and too narrow road lanes. Accident risk rates significantly increase for curves with a radius smaller than 200 m (Safetynet, 2009a). In addition to that, accident risk in curves is dependent on the extent to which geometry of individual curves fits with the design standards of the surrounding road environment. For instance, road sections where curves with more gentle design standards and higher radii are suddenly followed by a sharp curve appear to be very dangerous. Another well-known problem is the succession of a long tangent and a sharp curve (R. Elvik et al., 2009; Safetynet, 2009a). As indicated by Comte and Jamson (2000), curves at two-lane rural highways are most problematic given their lower design standards in comparison with those for freeways or urban streets.

In order to induce appropriate speed and lateral control in curves, a wide variety of additional infrastructural traffic control devices has been proposed such as signs (i.e., (dynamic) warning signs, advisory speed signs, (chevron) alignment signs and delineators) and pavement markings (i.e., directional arrows, centerline or shoulder rumble strips and (peripheral) transversal strips) (e.g. Charlton, 2004, 2007; Comte & Jamson, 2000; Federal Highway Administration, 2012; Hallmark et al., 2013; Katz, 2004; McGee & Hanscom, 2006).

Since this study focuses on the use of pavement markings, we will briefly elaborate on what are assumed to be the main working mechanisms behind this specific type of countermeasure. Pavement markings are primarily qualified as perceptual countermeasures (PCM), meaning they are intended to regulate driving behavior mostly by manipulating the visual driving scene, but sometimes also by means of additional auditory and/or tactile feedback (Godley, 1999). More specifically, the sensory feedback cues generated by pavement markings are meant to create particular illusionary effects such as the impression of increased motion or a lane narrowing effect. These illusions are not only aimed at assisting drivers in more optimally monitoring their speed and/or lateral control. In addition to that, they can also have an important alerting function (Godley, 1999; Thompson, Burris, & Carlson, 2006).

The impression of increased motion is often generated optically by means of a sequence of transverse colored lines at decreasing distances apart in the travel direction, thereby stimulating drivers to slow down while approaching a dangerous road section. In case of so-called transverse rumble strips (TRS) (cf. Figure 45 left panel), this optical effect is accompanied by auditory and tactile feedback to drivers (Godley, 1999). Although both field studies and simulator experiments have demonstrated the effectiveness of TRS as a speed reducing measure in the presence of intersections, rural-urban transitions and work zones (Godley, 1999; S. Jamson et al., 2010; Montella et al., 2010; Thompson et al., 2006), besides the study of Montella and colleagues (2015a), there is no clear evidence whether TRS are effective as a traffic calming measure nearby curves (Godley, 1999; McGee & Hanscom, 2006). Montella et al showed that TRS reduced speed before the curve, but this effect was not significant at the curve entry or along the curve.

Optical lane narrowing illusions can serve both purposes of speed reduction and lateral control and are induced by other pavement markings, such as chevron and herringbone patterns (HP) (Godley, 1999). Godley (1999) investigated the impact of both forward and backward pointing HP on driving behavior at intersections. Results obtained in a driving simulator indicated no significant speed reductions. An additional computer-based image evaluation task was conducted to assess whether the different HP created a lane narrowing illusion. Participants had to judge lane width of both lanes with and without the different HP. The backward pointing HP (cf. Figure 45 right panel) was able to induce a lane narrowing illusion, but only from a plan view, not from a driver's perspective view. More recently, Charlton (2007) investigated the usefulness of still another HP and focused on its application nearby curves. He only found effects on lateral position, not on speed.

In conclusion, various studies already examined the effect of pavement markings on driving behavior. Potential as a traffic calming measure has been found for TRS and HP. However, results for these two pavement markings are not conclusive and were obtained mostly when applied nearby intersections. This study will contribute to prior research by examining whether TRS and HP can regulate speed and/or lateral control in and nearby curves. The more precise objectives will be outlined below.

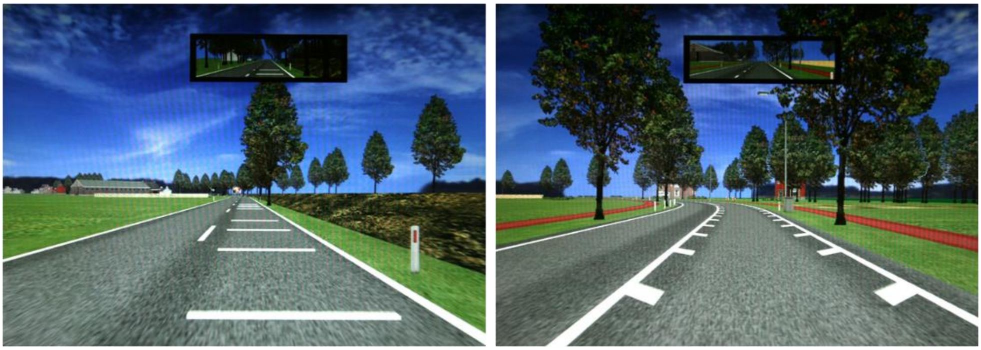


Figure 45 Simulator image of transversal rumble strips (left) and herringbone pattern (right)

4.1.2 Objectives

The primary objective of this study is to investigate the influence of transversal rumble strips (TRS) and a backward pointing herringbone pattern (HP) on both speed and lateral control in and nearby curv1es. Based on the literature review, the following hypotheses are formulated for this experiment:

- TRS stimulate drivers to slow down while approaching a dangerous curve.
- Optical lane narrowing illusions induced by the HP stimulate drivers to reduce their speed just before and along the curve section.
- The HP emphasize the lane boundaries and improve the lateral control along the curve. The effects of TRS on lateral control are expected to be rather limited.

For this purpose, the existing Flemish road network was screened for dangerous curves situated within a two-lane rural highway environment (cf. paragraph 4.1.3 C). As will be further highlighted under section C, the curves finally selected were replicated as realistic and detailed as possible in the driving simulator, following the so-called geo-specific database modeling approach as proposed and recommended by Yan, Abdel-Aty, Radwan, Wang, & Chilakapati (2008b). More detailed insight into the methodological design of this study will be provided below.

4.1.3 Methodology

A. Participants

Thirty-eight volunteers participated in the study. All gave informed consent. Six participants were excluded. Two did not finish the experiment due to simulator sickness and four were identified as outlier with a speed more than three inter-quartile distances either from the group's first or third quartile speed value 25%

(Q1) or 75% percentile (Q3) during 25% of the analysis section. Thus, 32 participants (20 men) between 18 and 54 years old (mean age 26; SD age 9.6; mean driving license: 7.0 years; SD driving license: 9.8 years) remained in the sample. All participants had (corrected to) normal vision. Gender and age were not taken into account as between-subject factors in the statistical analysis.

B. Driving simulator

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-base (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual, auditory and tactile feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images. Three projectors offer a resolution of 1024 × 768 pixels and a 60 Hz frame rate. The sound of traffic in the environment and of the participant’s car were presented. The data, which was collected at a 60 Hz frame rate, was interpolated to a 1 m distance interval before starting the data analysis.

C. Scenario

Curve selection and description

The search for candidate curves within the existing Flemish road network was based on the official Belgian accident database (1997-2007) (Federal Government Statistics Belgium, n.d.). Several queries were performed in order to select curves which could be considered as dangerous. For instance, curves had to be situated within a two-lane rural highway environment and curve accidents could not be related to causative factors such as the presence of intersections or roundabouts, alcohol, drugs, fatigue or bad weather conditions, etc. In addition, Google Earth satellite images and cross-sectional street views were analyzed to get a better idea of the surrounding road environment and to be able to evaluate to what extent curve geometry was (or was not) in line with the road’s overall trajectory. Finally, detailed accident maneuver diagrams were analyzed and the research team went *in situ* to make a final selection.

The result was two left-oriented compound curves, both preceded by a long tangent and characterized by complex geometrical alignment with radii of different sizes combined with each other. The detailed accident maneuver diagrams of both curves showed both run-off-road and head-on collisions. More detailed information on these two curves can be found under Figure 46. As further outlined below, these two curves, together with their mirror images (i.e., right-oriented) were replicated as realistic and detailed as possible in the simulator.

Curve development

In programming the two selected curve sites, we closely followed a procedure called geo-specific database modeling, as it was described and recommended by Yan et al. (2008b). Geo-specific database modeling is defined by the authors as replicating a real-world driving environment in a simulated virtual world (Yan et al., 2008b) and is to be differentiated from simulator research where often, the driving scenarios offered to participants are fictive (Fisher et al., 2011). As the purpose is to reproduce an existent driving scene as detailed and realistic as possible, the procedure for curve programming was based on a combination of blueprints, AutoCAD simulations, and detailed field measurements performed by the research team. Pictures of the two real world curve scenes and their virtual replica can be found under Figure 46.

Scenario design

Once the curve sections were finalized, the overall scenario could be programmed (for a visual overview, we refer to Figure 48). As can be seen, the experimental scenario of 16.2 km is a systematic combination of the curve sections of interest with a set of filler pieces, differing from curve sections with respect to design, speed limit and surrounding environment and meant to provide some variation while driving.

Combining the different manipulated factors, i.e., curve location (A vs. B), direction (left vs. right) and condition (control vs. TRS vs. HP), twelve curve sections were created and randomized over a 2×2×3 full within-subject design with 6 curves per trip of 16.2 km and the order of conditions, curve sections and filler pieces counterbalanced over participants. The directions of the curves in Figure 48 are thus only one of the possible randomized combinations of the 12 curves.

TRS were located at a range from 150 to 66 m before the curve and were 0.50 m in depth and 3 mm thick (Vanduyver & Depestele, 2002, p. 303). The impression of increased motion is generated optically by means of the sequence of transverse lines at decreasing distances apart in the travel direction (see Figure 47). Thereby, drivers are stimulated to slow down while approaching the dangerous curve. Both auditory and tactile feedback were provided by the sound equipment and the steering wheel of the driving simulator each time participants drove over a strip. The backward pointing HP reached from curve entry to exit and appeared at both sides of participants' driving lane (i.e., at the edge- and centerline). Both markings are illustrated in Figure 45 and Figure 47.

a

	Loc A	Loc B		Loc A	Loc B		Loc A	Loc B
Radius 1	170m	169m	Length 1	17m	51m	Total curve length	130 m	116 m
Radius 2	94m	92m	Length 2	29m	19m	Speed limit	90 kph	70 kph
Radius 3	161m	97m	Length 3	46m	21m	Road lane width	3.2m	2.8m
Radius 4	219m	688m	Length 4	38m	25m	Bicycle facilities	Yes	No

Curve location A **Curve location B**

b

c

Figure 46 (a) Curve properties; Curve location A and B: (b) real world image nearby curve, (c) simulator image before curve

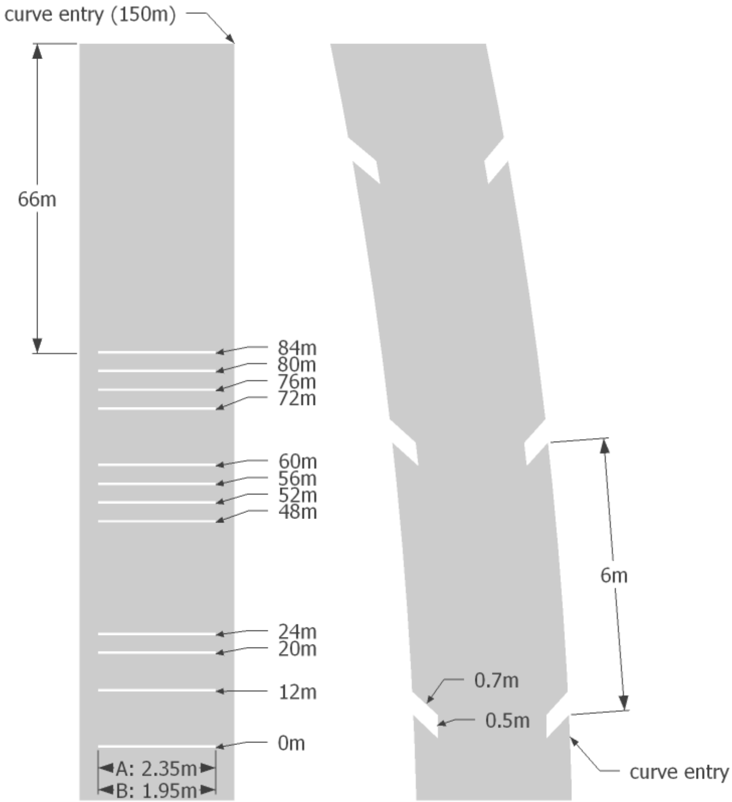


Figure 47 Geometric characteristics TRS (left) and HP (right)

Filler pieces were always 1,000 m long, starting with a stretch of 100 m falling still outside a built-up area (speed limit: 70 kph), succeeded by an inside built-up area of 800 m (speed limit: 50 kph), and ending with another stretch of 100 m outside the built-up area (speed limit: 70 kph or 90 kph, depending on which of the curves (i.e., curve location A or B) followed). Study participants met some random traffic in the opposite direction, except from 400 m before the curve until the next filler piece. This was done mainly in order not to influence participants' self-selected speed and/or lateral position in the curves. Weather conditions were sunny and dry.

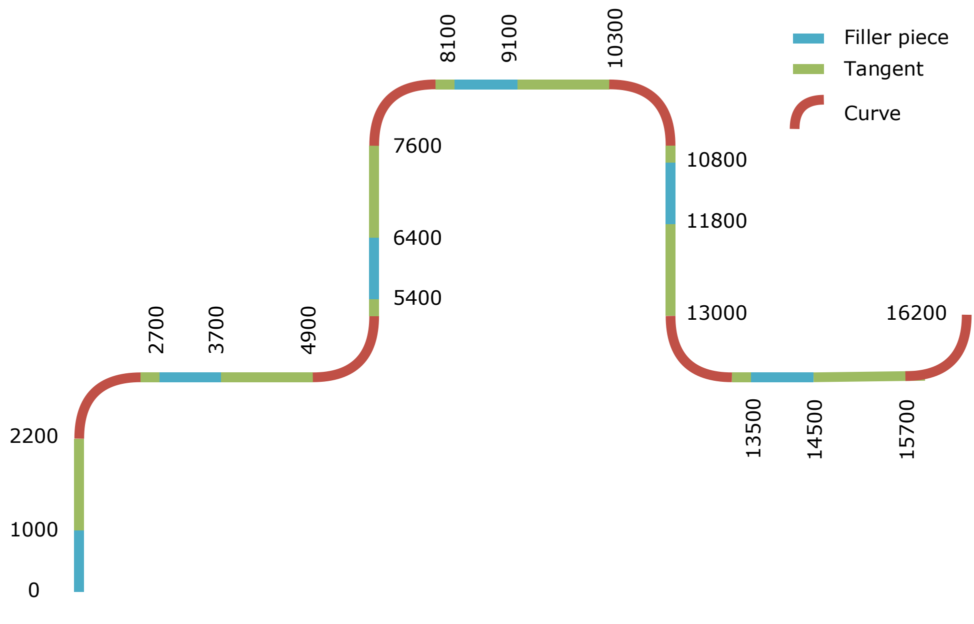


Figure 48 Scenario overview

D. Procedure

Participants were asked for their informed consent and to fill out a form with their personal data (e.g. gender, date of birth). The simulator session consisted of a practice session and an experimental session. During two practice trips of 4.5 km with a variety of traffic situations (i.e., urban areas, sharp curves, traffic lights) drivers acquainted themselves with the driving simulator. The experimental session contained two trips of the 16.2 km long experimental scenario (see paragraph 4.1.3 C). Subjects were instructed to "drive as they normally do". Drivers did not receive specific instructions about the speed limits (which were different at both curve locations). Based on the speed limit signs in the scenario and the Belgian traffic laws drivers can be expected to be able to derive the speed limit on the different road segments.

E. Data collection and analysis

Dependent measures

Driving performance measures for both speed and lateral control were recorded (Rosey et al., 2008). More in detail, speed enforcement was assessed by means of mean speed [kph] and mean acceleration and deceleration (acc/dec) [m/s²] and mean lateral position (LP) [m] was used as measure for lateral control.

We motivate the selection of these specific parameters as follows: among the different speed-related parameters known in the literature, mean speed is used as a standard measure for safe driving (SafetyNet, 2009). Mean longitudinal acc/dec in turn, is considered to be a good indicator of both driving safety and comfort. Large mean acc/dec increases the risk for skidding accidents because of reduced tire-road surface friction (PIARC, 2003). In addition, the chance for rear-end collisions augments because unstable mean acc/dec means abrupt changes in speed which are difficult to be safely anticipated to by other drivers (Dewar & Olson, 2007).

Lateral control relates more to managing the vehicle's horizontal position within the driving lane. Lack of a harmonized lane position is a primary cause of single-vehicle run-off-road accidents and head-on collisions, particularly in curves (Rosey et al., 2008; Yan et al., 2008b). Mean values for lateral position are frequently used as indicators for lateral control (Auberlet et al., 2012; Bella, 2013; Charlton, 2007; Coutton-Jean et al., 2009; Räsänen, 2005; Rossi et al., 2013a).

Data analysis

Sections that were to be statistically analyzed combined the tangent (1,200 m) followed by one of the curves selected and ended again with tangents of 300 to 375 m. Data analyses for mean speed, mean acc/dec and mean LP are based on values obtained at ten measurement points along the driving scenario (see Figure 49). Since this study focuses on driving behavior in and nearby curves, the scenario segments that were analyzed went from 500 m before the curve until 100 m after.

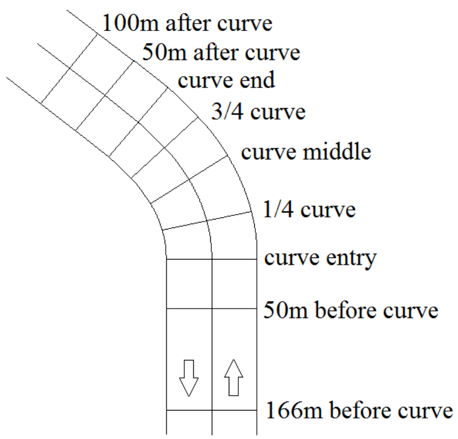


Figure 49 Plan view of analysis section with measurement point (first point at 500m before curve)

A 2 (direction: left, right) × 3 (condition: control, TRS, HP) × 10 (measurement point) within-subject multivariate analyses of variance (MANOVA) with additional post-hoc univariate tests and ANOVA's were conducted on the speed and lateral control parameters for each curve location separately. Significant interactions between within-subject factors were only of interest when the factor Measurement point was part of the interaction since parameter values were not averaged for the ten measurement points. For all analyses, p-value was set at 0.05. For MANOVA's F- and probability values are reported. ANOVA's were corrected for deviation from sphericity (Greenhouse-Geisser epsilon correction) and the corrected F- and probability values are mentioned.

4.1.4 Results

The results are described for the three driving parameters under investigation at curve location A and curve location B separately.

A. Curve location A

Table 14 presents both multi- and univariate statistics for mean speed, mean acc/dec and mean LP at curve location A. The results of the MANOVA showed a significant main effect of *Direction*, *Condition* and *Measurement point*. In addition, the interactions of *Direction* × *Measurement point* and *Condition* × *Measurement point* have a significant effect on the three driving parameters. The subsequent univariate statistics are described below.

Table 14 Multivariate and univariate statistics for mean speed, mean acc/dec and mean LP at location A

Variable	*MANOVA for mean speed, mean acc/dec and mean LP*		*Univariate statistics*					
			Mean speed		*Mean acc/dec*		*Mean LP*	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Direction	44.5	**<.0005**	<1	0.891	1.6	0.210	123.8	**<.0005**
Condition	3.8	**0.002**	8.9	**0.001**	5.5	**0.007**	<1	0.993
Measurement point	36.3	**<.0005**	164.1	**<.0005**	83.3	**<.0005**	2.0	*0.099*
Direction × Condition	<1	0.946						
Direction × Measurement point	12.2	**<.0005**	1.4	0.221	2.8	**0.032**	90.6	**<.0005**
Condition × Measurement point	5.5	**<.0005**	10.0	**<.0005**	6.9	**<.0005**	<1	0.541
Direction × Condition × Measurement point	1.1	0.356						

p ≤ 0.05; *p ≤ 0.1*

Table 15 Multivariate and univariate statistics for mean speed, mean acc/dec and mean LP at location B

Variable	*MANOVA for mean speed, mean acc/dec and mean LP*		*Univariate statistics*					
			Mean speed		*Mean acc/dec*		*Mean LP*	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Direction	18.0	**<.0005**	1.1	0.296	<1	0.483	48.4	**<.0005**
Condition	5.6	**<.0005**	7.2	**0.002**	11.9	**<.0005**	1.0	0.370
Measurement point	33.9	**<.0005**	128.8	**<.0005**	58.3	**<.0005**	4.7	**0.001**
Direction × Condition	3.1	**0.007**	<1	0.573	1.6	0.220	6.5	**0.003**
Direction × Measurement point	11.1	**<.0005**	2.1	*0.084*	1.0	0.407	73.7	**<.0005**
Condition × Measurement point	3.0	**<.0005**	6.1	**<.0005**	2.0	*0.056*	1.2	0.307
Direction × Condition × Measurement point	1.2	0.191						

p ≤ 0.05; *p ≤ 0.1*

Mean speed

Figure 50 shows the mean speed values in each of the ten measurement points, separated per test condition, but irrespective of the curve direction because the factor *Direction* was not significant in the univariate statistics for mean speed. Besides the significant main effect of *Condition* and *Measurement point*, the interaction effect of *Condition* × *Measurement point* was also significant. Therefore, we can conclude that mean speed varied across the ten measurement points in function of the three test conditions.

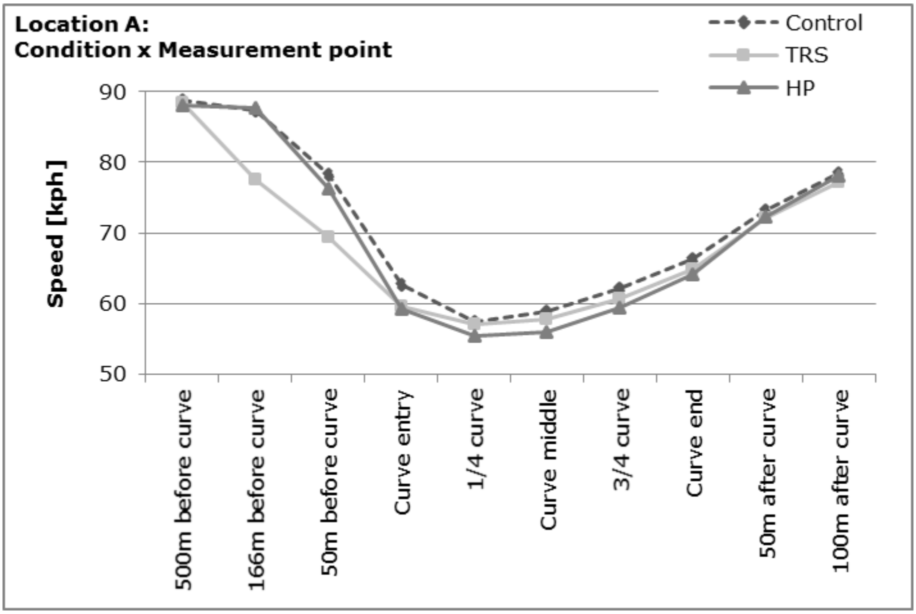


Figure 50 Mean speed for the interaction of Condition × Measurement point at curve location A

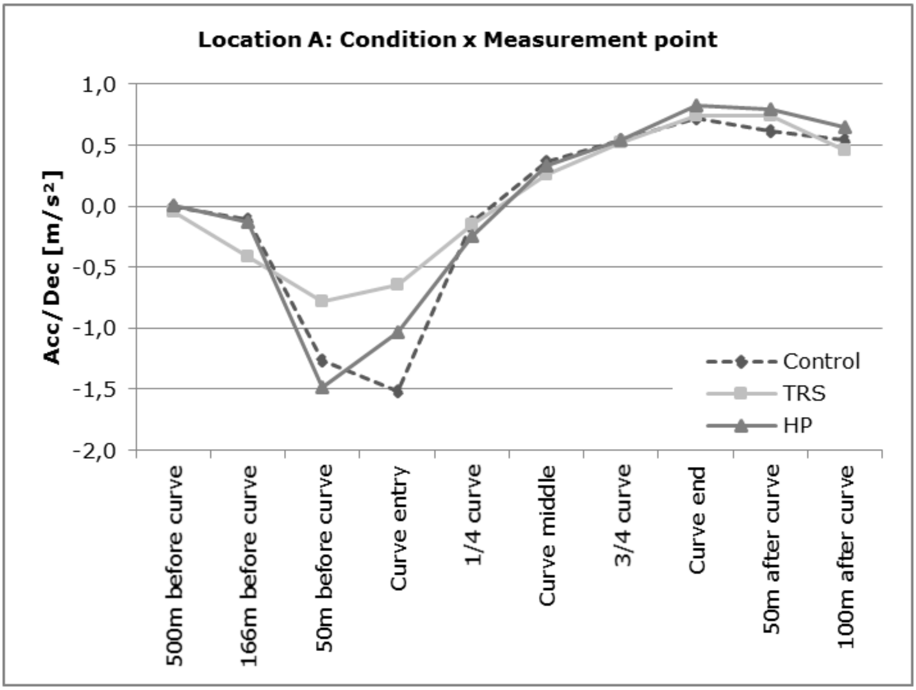
Post hoc analysis showed that mean speed was 8.9 to 9.8 kph lower at 166 and 50 m before the curve in the TRS condition compared to the control condition. The TRS generated also a lower mean speed of 6.9 to 10.1 kph compared to the HP at these two measurement point (166 m before curve: $F_{(1, 44)} = 31.6$, $p < .0005$, $\eta_p^2 = 0.505$; 50 m before curve: $F_{(2, 58)} = 20.2$, $p < .0005$, $\eta_p^2 = 0.395$). In spite of this speed reduction effect of the TRS on the tangent, mean speed reached the same level as the control and HP condition from the curve entry on. The HP on the other hand generated a (marginal) lower mean speed at the curve entry, curve middle and ¾ curve of 2.5 to 3.5 kph compared to the control condition (curve entry: $F_{(2, 54)} = 3.2$, $p = 0.057$, $\eta_p^2 = 0.092$; curve middle: $F_{(2, 59)} = 3.1$, $p = 0.054$, $\eta_p^2 = 0.091$; ¾ curve: $F_{(2, 61)} = 3.4$, $p = 0.040$, $\eta_p^2 = 0.100$). Further analysis showed that for the three conditions highest mean speed was registered at 500 m before the curve where it came close to the speed limit of 90 kph. The lowest speeds were recorded at ¼ curve. Drivers started to speed up again after the curve middle.

To summarize, both the TRS and the HP generated significant speed reductions compared to the control condition. The TRS did so on the tangent preceding the curve while for the HP, the speed reduction effect was induced only when entering the curve and proceeded until ¾ curve.

Mean acc/dec

An overview of the results for mean acc/dec can be found under Figure 51. More specifically, the left panel depicts the significant interaction of *Condition* × *Measurement point* and contains one plot per test condition, representing values for mean acc/dec that were first averaged over the two curve directions and subsequently set out at each of the ten measurement points. A comparison of the three conditions showed that significant differences for mean acc/dec could be detected at three specific measurement points, i.e., (1) at 166 m before the curve ($F_{(2, 50)} = 19.3$, $p < .0005$, $\eta_p^2 = 0.383$), (2) at 50 m before the curve ($F_{(2, 55)} = 9.8$, $p < .0005$, $\eta_p^2 = 0.241$), and (3) at curve entry ($F_{(2, 59)} = 9.2$, $p < .0005$, $\eta_p^2 = 0.228$). While at 166 m in advance of the curve, mean deceleration was significantly higher for curves with TRS than for curves with a HP or control curves, the opposite counted for what happens at 50 m before the curve and at curve entry. At these two measurement points, drivers decelerated significantly stronger in curves with a HP and in control curves than in curves provided with TRS. Further analysis indicated that the highest mean deceleration was recorded at the 50 m before the curve in the TRS (mean = -0.786, SD = 0.144) and HP condition (mean = -1.486, SD = 0.170), whereas maximum deceleration in the control condition was reached at the curve entry (mean = -1.516, SD = 0.188). In order to be able to evaluate the extent to which these high mean deceleration rates can be considered as acceptable in terms of safety, we performed a one-way sample T-test to compare them with the -0.85 m/s^2 value proposed by Lamm and Choueiri (1987) and Altamira and colleagues (2014) as a recommended design guideline. It resulted from this test that the maximum mean deceleration was significant higher at the curve entry in the control condition ($t = -3.5$; $p = 0.001$) and at 50 m before the curve in the HP condition ($t = -3.7$; $p = 0.001$).

Figure 51 (right panel) contains one plot per curve direction with values for mean acc/dec at each of the ten measurement points, representing the significant interaction effect of the factors *Direction* × *Measurement point*. The values for mean acc/dec were thus averaged over the three test conditions. This graph shows almost the same pattern in deceleration and acceleration maneuvers for both curve directions. However, post-hoc analysis showed that deceleration was significantly stronger in the left curves at the curve entry compared to the curves in right direction ($F_{(2, 59)} = 9.2$, $p < .0005$, $\eta_p^2 = 0.228$).



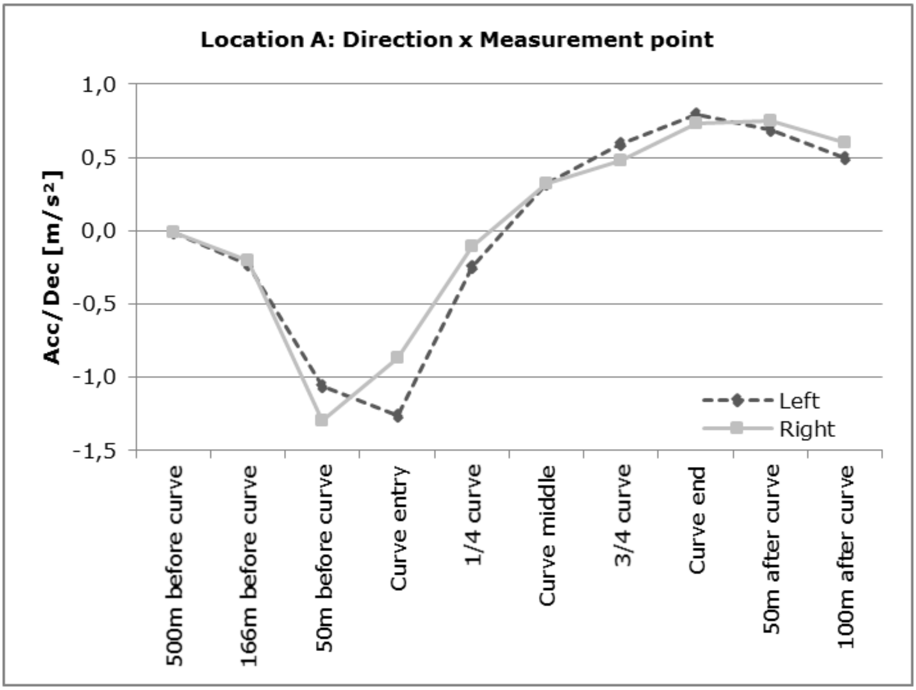


Figure 51 Mean acc/dec for the interaction of Condition × Measurement point (left) and Direction × Measurement point (right) at curve location A

Mean LP

An overview of the results for mean LP can be found under Figure 52. Mean LP in the three test conditions is depicted for the seven measurement points starting at 50 m before the curve and ending at 50 m after the curve. For both curve directions, drivers drove closely to (the right side of) the middle of their driving lane at the straight road sections before and after the curve. However, between 50 m before the curve and ¼ curve drivers started to move closer to the centre of the curve. For left curves, this means that drivers drove closer to the middle line, and thus closer to the opposite travel lane. While in right curves, mean LP was closer to the edge line. This decentralized mean LP was preserved until ¾ curve after which drivers shifted back to the right side of the middle of their driving lane. This curve lengthening effect (Fisher et al., 2011) in opposite direction in both curve directions was also confirmed by the statistical analysis showing a significant interaction effect of *Direction* × *Condition*. It is important to note that the differences between the three test conditions were minimal (the factor *Condition* as main or interaction effect was not significant) and therefore hard to distinguish in the figures.

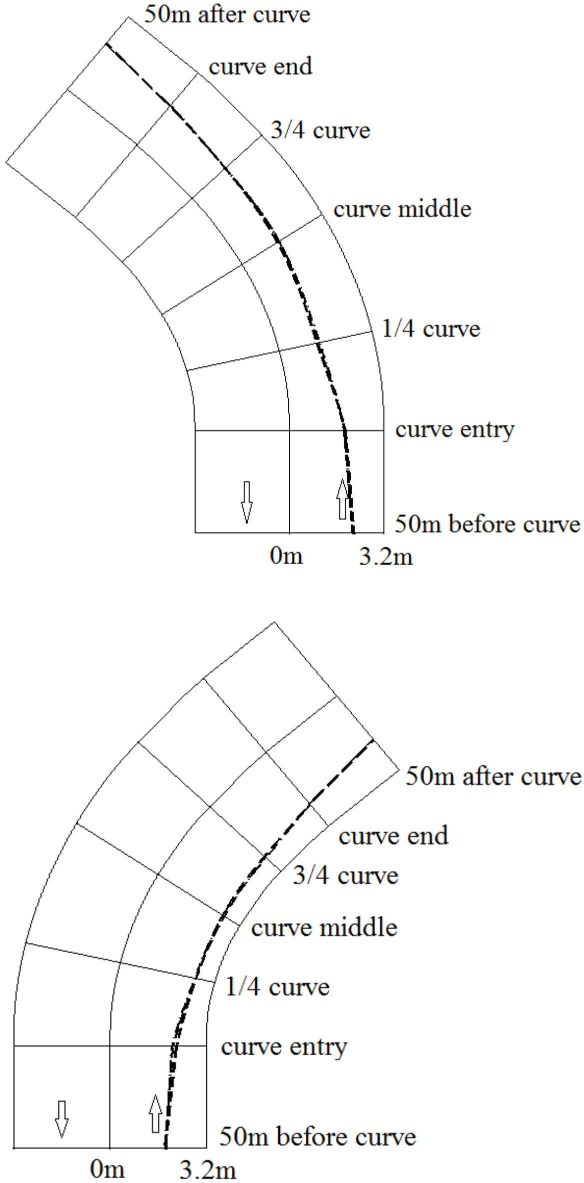


Figure 52 Mean LP at 7 measurement points for the left and right curve in the three test conditions at curve location A

B. Curve location B

The same MANOVA and univariate analysis were performed for curve location B and the results are shown in Table 15. The significant main effects of the factors *Direction*, *Condition* and *Measurement point* are complemented with three significant two-way interaction effects of *Direction* × *Condition*, *Direction* × *Measurement point* and *Condition* × *Measurement point*. The subsequent univariate statistics are described below.

Mean speed

The significant interaction effect of *Condition* × *Measurement point* is depicted in Figure 53 and shows one plot for each test condition, representing values for mean speed that were first averaged over the two curve directions and subsequently set out at each of the ten measurement points. Post hoc analysis showed that the TRS generated significant lower mean speeds compared to the control condition from 166 m before the curve until the curve middle. The difference in mean speed between the TRS and the control curve ranged between 5.3 and 2.3 kph. In addition, TRS generated a mean speed at 166 m before the curve which was 6.2 kph lower compared to the HP. This HP reduced mean speed also significantly compared to the control condition starting from the curve entry until the curve end. Speed differences ranged between 2.2 and 2.8 kph (166 m before curve: $F_{(2, 48)} = 15.0$, $p < .0005$, $\eta_p^2 = 0.326$; 50 m before curve: $F_{(2, 52)} = 3.4$, $p = 0.050$, $\eta_p^2 = 0.098$; curve entry: $F_{(2, 62)} = 9.0$, $p < .0005$, $\eta_p^2 = 0.224$; ¼ curve: $F_{(2, 61)} = 7.5$, $p = 0.001$, $\eta_p^2 = 0.194$; curve middle: $F_{(2, 62)} = 7.2$, $p = 0.002$, $\eta_p^2 = 0.187$; ¾ curve: $F_{(2, 58)} = 6.3$, $p = 0.004$, $\eta_p^2 = 0.169$; curve end: $F_{(2, 60)} = 5.1$, $p = 0.010$, $\eta_p^2 = 0.140$).

At 500 m before the curve, mean speed was the same in the three test conditions and was slightly higher than the speed limit of 70 kph. Although mean speed was rather constant from the curve entry until the ¾ curve, minimum speed was reached at ¼ curve in the control curve and in the curve with TRS, while minimum mean speed was measured at the curve middle in the condition with HP. Drivers started to speed up again after ¾ curve.

To summarize, both the TRS and the HP generated significant speed reductions compared to the control condition. The TRS did so from 166 m before the curve until the curve middle, while for the HP the speed reduction effect was induced only when entering the curve but preserved until the curve end.

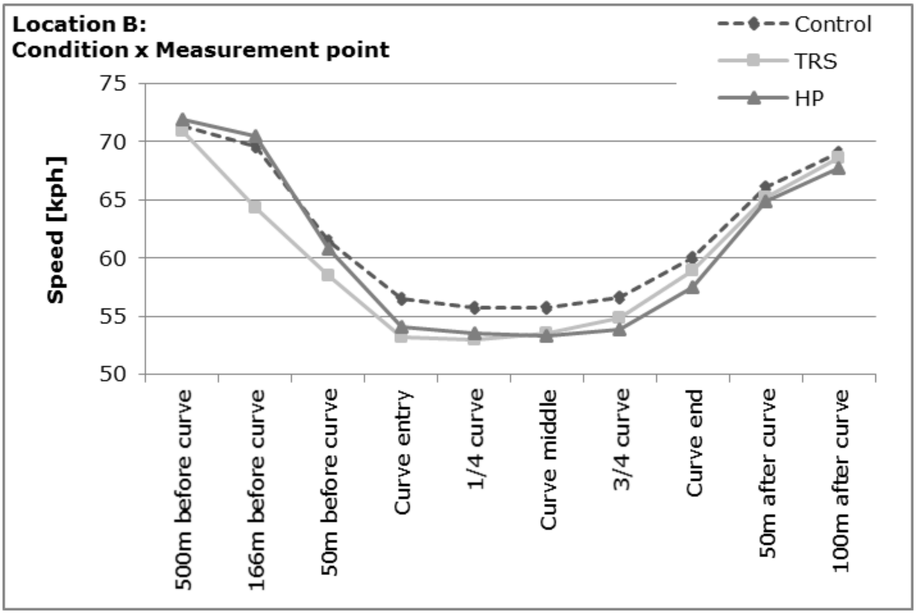


Figure 53 Mean speed for the interaction of Condition × Measurement point at curve location B

Mean acc/dec

The univariate analysis for mean acc/dec showed a significant main effect of *Condition* and *Measurement point* and a marginal significant interaction of these two factors. Figure 54 shows the mean acc/dec values for the marginal interaction of *Condition* × *Measurement point*. Post hoc analysis revealed significant larger deceleration values for the control condition (marginal effect) and HP compared to the condition with TRS at 50 m before the curve ($F_{(2, 54)} = 6.2$, $p = 0.005$, $\eta_p^2 = 0.167$). In addition, at ¼ curve drivers were still decelerating in the curve with HP, while mean acc/dec were slightly positive (i.e., accelerating) in the TRS condition ($F_{(2, 50)} = 4.0$, $p = 0.031$, $\eta_p^2 = 0.115$). Furthermore, there were no significant differences in mean acc/dec between the three test conditions. Additional one-way T-tests comparing the maximum deceleration with the value of -0.85 m/s² from Lamm and Choueiri (1987) confirmed Figure 54 in which mean acc/dec was never smaller than -0.85 m/s².

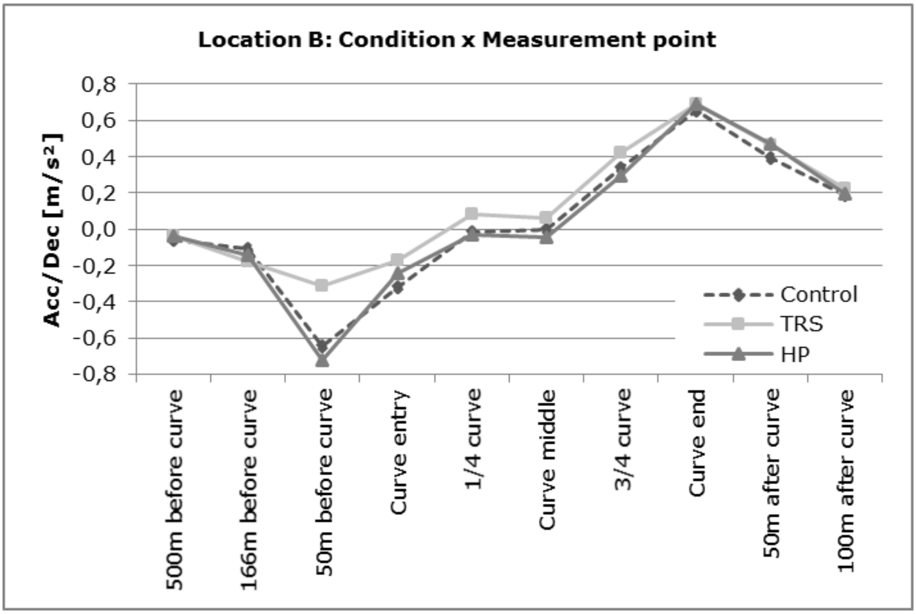


Figure 54 Mean acc/dec for the interaction of Condition × Measurement point at curve location B

Mean LP

Figure 55 shows the mean LP at seven measurement points (from 50 m before the curve until 50 m after the curve) at curve location A for the left and right curve. The same curve lengthening effect was also found in the curve at location B and statistically founded by the significant interaction effect of *Direction* × *Measurement point*. In other words, drivers drove closer to the edge line while approaching and entering left curves while they shifted to the centerline nearby the curve middle and then closer back again to the edge line at the end of the curve. The opposite was found for right curves.

Besides the main effects of *Direction* and *Condition*, there was also an interaction effect of *Direction* × *Condition*. The interaction effect indicated that in the left curve ($F_{(2, 59)}$ = 6.3, p = 0.004, η_p^2 = 0.168), averaged over the ten measurement points, mean LP was (marginally) significant closer to the lane edge in the control condition compared to the TRS (p = 0.083) and HP (p = 0.011). There were no significant differences between the three test conditions in the right curve ($F_{(2, 60)}$ = 2.2, p = 0.118, η_p^2 = 0.067).

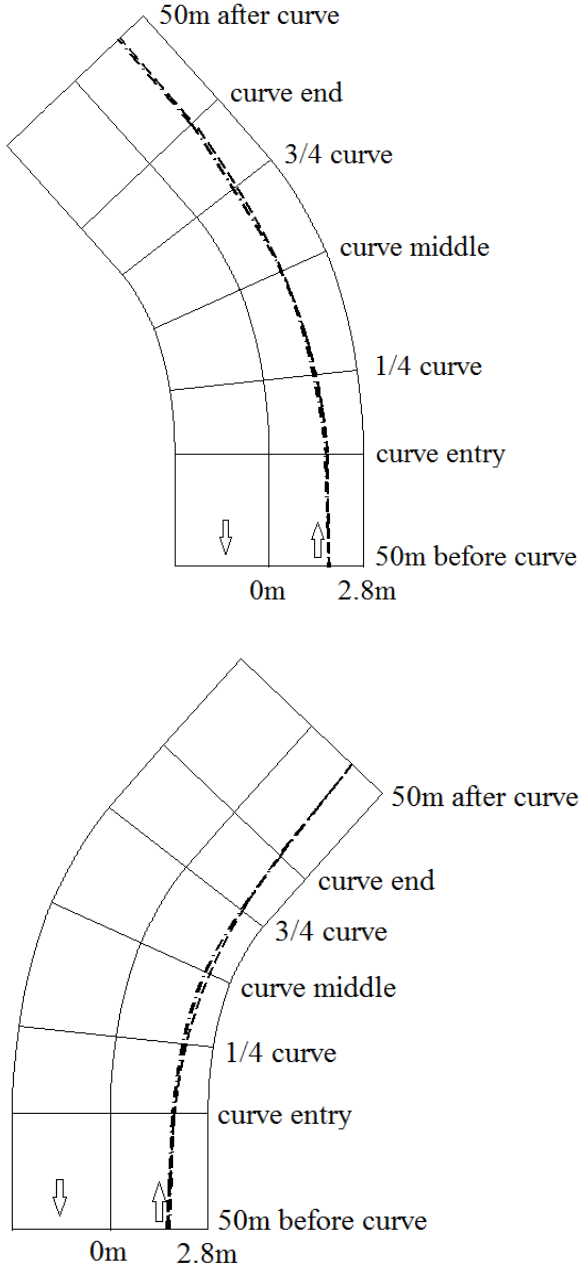


Figure 55 Mean LP at 7 measurement points for the left and right curve in the three test conditions at curve location B

4.1.5 Discussion

In this study, two real-world curves with strong indications of an existing safety problem were identified and replicated in the simulator. Interestingly, these were two compound curves both (1) situated within a rural two-way road environment, (2) following a long tangent, and (3) characterized by complex geometrical properties. Besides these similarities, the two curves in this study were substantially distinct in terms of (1) speed limit (70 kph vs. 90 kph), (2) cross-sectional view (different lane widths; with vs. without separate cycle lanes; with vs. without a line of trees nearby the edge lines), and (3) horizontal alignment (different length; different curvature structure). Therefore we considered both curve location in two separate analysis. However, in this discussion section we try to give an overview of the several analysis. The mutual dissimilarities can partially explain why differences in both speed and lateral control could be found between the two curves.

A. Driving behavior compared over the two curves

Overall, mean speed was higher at curve location A than at curve location B which is attributable to the higher speed limit at location A (90 kph vs. 70 kph at location B). Irrespective of the test condition, mean speed was not constant along the curve section. Participants started to slow down on the tangent between 166 and 50 m before the curve entry in the control and HP condition, whereas the TRS induced a speed decrease already before 166 m before the curve entry due to the presence of the TRS (located between 150 and 66 m before the curve). Their minimum speed was reached around ¼ curve and they started to accelerate again along the curve (curve middle at location A and ¾ curve at location B). This acceleration maneuver was less strong that the deceleration maneuver while approaching the curve at location A. However, at location B mean deceleration and acceleration was rather similar. These results are in line with the findings of Montella and colleagues (2015; 2015a) who investigated continuous speed profiles in curves by means of a driving simulator. Nevertheless, it is important to note that the study of Montella et al. used curves in which a spiral curve was followed by curves with a contact radius, whereas this simulator study replicated two compound curves. The different curve radii in different lengths might also have influenced the non-constant speed profile along the curves.

With respect to mean deceleration, drivers not only decelerated till further into the curve at location A, they also reduced their speed more strongly. At its peak nearby curve entry, values for mean deceleration at location A even significantly exceeded the rate of -0.85 m/s² recommended by Lamm and Choueiri (1987). Even though others proposed higher acceptable values up to -1.34 and -1.8 m/s² (Hu & Donnell, 2010; Zuriaga, García, Torregrosa, & D’Attoma, 2010), which was more within the range of our results. Contrary to that, for curves at location B, maximum deceleration was reached earlier (i.e., 50 m before the curve) and remained below the more stringent value of -0.85 m/s². One possible reason for these differences in terms of deceleration might be that, over the different conditions, the absolute speed reduction at location A was larger compared to location B. At location A drivers had to decelerate from 88 kph at 500 m before the curve to 60 kph at curve entry in order to safely enter the curve. The speed reduction at location B was limited to 16 kph (from 71 kph to 55 kph). This is reflected in a substantially higher maximum speed reduction between tangent and curve at location A (speed difference = 32 kph) when compared to location B (speed difference = 17 kph). When considering some of the international design standards as listed up by Lamm, Mailander, & Psarianos (1999), these values would indicate poor design quality for location A and fair quality at location B. Anyway, excessive and abrupt deceleration should be avoided both in terms of safety (the risk for skidding accidents would increase drastically, especially under wet conditions) as in terms of maintenance (increased tire friction puts more pressure on the road surface) (PIARC, 2003).

At both curve locations as well as in both directions, drivers drove closer to the inside road edge nearby the curve middle. This confirms results reported in other studies (Dijksterhuis, Brookhuis, & De Waard, 2011; Räsänen, 2005; Robertshaw & Wilkie, 2008). This so called 'curve lengthening' (Fisher et al., 2011) was stronger present in the right curves compared to the left curves. A possible reason for this finding might be related to the fact that the simulator mock-up did not have a passenger side which induced an underestimation of the vehicle width by the participants and resulted in driving more to the right side of their lane.

B. Effect of TRS and HP on driving behavior

The primary objective of this study was to examine the effect of TRS and a backward pointing HP on speed and lateral control in and nearby curves. Compared to the control condition, both TRS and HP generated significant speed reductions. Yet, compared to the HP, TRS evoked lower speeds earlier (166 m before the curve vs. at curve entry) but ebbed away when entering the curve while the speed reduction effect of the HP persisted until reaching ¾ curve or curve end. These findings are in line with the two first hypotheses which were formulated in the paragraph 4.1.2 and the results of the study of Montella et al (2015a).

The size of the speed reduction compared to the control condition was larger for TRS than for the HP. The absolute higher driving speed on the tangent might result in a higher speed reduction potential on that part on the road compared to a curve section where drivers already decreased their speed compared to the tangent. Besides the visual input of both pavement markings, the tactile and auditory feedback of the TRS might have an additional trigger to decrease driving speed. According to the power model for speed and accidents (R. Elvik, 2009, p. 58), mean speed reductions obtained for TRS in this study (i.e., -5.3 to -9.8 kph at

166 m before the curve; -3 to -8.9 kph at 50 m before curve) would result in a decrease of 18.7 to 39.1% for fatal accidents and 7.8 to 17.6% for injury accidents compared to the control condition. The HP has the potential to reduce the number of fatal and injury accidents with 17.9 to 26.4% and 6.6 to 9.6% respectively, depending on the exact position of accidents along the curve (i.e., entry, ¼, middle, ¾ or end).

The results for mean acc/dec corresponded to this finding with the highest deceleration rates at 166 meters before the curve for TRS versus 50 m before the curve for HP. Important in terms of safety is that, deceleration until the curve entry was more stable with TRS than with HP. Parameters for lateral control were not significantly affected by TRS or HP. The absence of an influence of TRS on the mean LP was also in line with the respective hypothesis. However, we expected an improved lateral control in the HP condition because this pavement marking emphasizes the lane boundaries. This hypothesis is not supported by the results.

In the control and HP condition, mean speed started to decrease significantly between 166 and 50 m before the curve at both curve locations. This might be related to the finding that drivers start to explore curves between 100 and 30 m before the curve entry (references in Milleville-Pennel, et al., 2007). The TRS, which were located between 150 and 66 m before the curve entry, induced the participants to reduce their speed already at 166 m before the curve. The lower driving speed on a tangent equipped with TRS gives drivers more time to generate the right expectations about the oncoming curve and the related risks and attentional demands. The lower driving speed just before entering the curve does not force them to suddenly adapt their behavior near the curve entry or along the curve. This is an important issue because accidents occur primarily at both the curve entry or the curve end (PIARC, 2003). In addition, Lee and his colleagues (2002) found for rear-end collisions that early warnings (TRS on tangent) more quickly can activate drivers to intervene in their driving behavior, compared to no (control condition) or late warnings (HP along the curve).

Although this paper only investigates the effect of the TRS and the HP in combination with two dangerous curves which were both preceded by a long tangent (i.e., 1,200 m), it is important to mention that that the different locations of both markings (TRS: between 166 and 50 m before the curve entry; HP: from curve entry until curve end) might result in different driving behavior in curves with a shorter tangent. The study of Matthews and Barnes (1988; in R. Elvik et al., 2009, p. 241) showed that tangents with increasing length (i.e., above 400 m) result in higher accident risk compared to curve locations with shorter tangents (i.e., below 400 m) due to higher speeds on longer tangents. As a result, many of the potential dangerous curves might have a long tangent and TRS have the potential to improve road safety especially in the case of high accident rates at curve entry. Dangerous curves with short tangents might experience the best safety potential of the HP as this pavement marking has its main impact just before and along the curve.

4.1.6 Limitations and future research

Besides the numerous advantages of driving simulator research, external validation is an often mentioned issue. Moving-base driving simulators score in general the best because their degree of realism and rendering of real life driving is better than fixed-base simulators (Bella, 2009). Nevertheless, several studies demonstrated serious indications that fixed-base simulators are also perfectly adequate to examine geometric design issues (Charlton, 2004, 2007; Bella, 2007, 2008; Keith et al., 2005; Federal Highway Administration, 2007; Calvi et al., 2012). In addition, the fixed-base simulator used in this study is equipped with a 180° field of view, which satisfies the prescribed minimum of 120◦field of view for the correct estimation of longitudinal speed (Kemeny and Panerai, 2003).

With respect to (the effect of) additional pavement markings in dangerous curves, further research could focus on different geometric design configurations, the tangent length, the location of the pavement markings with respect to the curve and a combination of various pavement markings and other additional traffic control devices such as signs.

4.1.7 Conclusion and recommendations

Considering the results for the different behavioral parameters for both speed and lateral control, both TRS or HP generated a significant speed reduction. The TRS was the most effective on the tangent and the resulting lower driving speed gave participants more time to right expectation about the upcoming curve. The HP, on the other hand, reduced driving speed along the curve. The recommendation about which pavement marking is the most effective should therefore depend on the exact accident location nearby or in the curve. When accidents occur primarily near the curve entry, TRS is recommended because this measure reduces speed before entering the curve. The HP has the potential to reduce accidents at the curve end because it keeps driving speed at a lower level along the curve. In addition, TRS might have the highest benefits on curves with long tangents (such as the curves in this experiment) as TRS have the potential to reduce the high driving speeds which are often related to long tangents compared to shorter tangents. Furthermore, this experiment showed a more stable deceleration maneuver towards the curve when TRS were implemented on the tangent. In order to avoid that drivers accelerate again between the TRS and the curve it is important that there is a visual link between the TRS and the curve which was the case in this configuration where the tangent was equipped with TRS between 166 and 50 m before the curve entry.

Despite the favorable implications in terms of road safety, Dewar and Olson (2007) warn for the potential negative side effects of both pavement markings such as noise, rapid wear, disruption of drainage and reduced tire-road surface friction. Furthermore, the experiment showed that the pavement marking produce no significant effects on lateral control parameters. Even though this is not the primary function of TRS or HPs, this finding should warrant policy makers not to consider these two road markings as a countermeasure in curves where accidents are mainly due to inappropriate lateral control. Finally, we advise policy makers to make a good selection of potential dangerous curves to avoid excessive implementation.

4.2 A DRIVING SIMULATOR STUDY ON THE EFFECT OF TRANSVERSAL RUMBLE STRIPS LOCATED NEARBY DANGEROUS CURVES UNDER REPEATED EXPOSURE

This chapter is based on:

Ariën, C.; Brijs, K.; Vanroelen, G.; Ceulemans, W.; Jongen, E.M.M.; Daniels, S.; Brijs, T.; Wets, G. (n.d.) A driving simulator study on the effect oftransversal rumble strips located nearby dangerous curves under repeated exposure. Submitted for first review in *European Journal of Transport and Infrastructure Research* [web of science: 5 year impact factor 1.144].

Proceedings:

Ariën, C.; Brijs, K.; Vanroelen, G.; Ceulemans, W.; Jongen, E.M.M.; Daniels, S.; Brijs, T.; Wets, G. (2014) *A driving simulator study on the effect of transversal rumble strips located nearby dangerous curves under repeated exposure.* In: Proceedings of 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014, Krakow (Poland), July 19-23, 2014.

Abstract

Objective: This study examined drivers' behavior nearby dangerous curves when they are repeatedly exposed to the same transversal rumble strips which were located on the tangent before the curve.

Method: During a period of five successive days, sixteen participants completed a 17km test-drive in a driving simulator with four dangerous curves (two without and two with transversal rumble strips) in a within-subjects design. The selection of these curves was based on the official Belgian accident database and both curves were replicated in the driving simulator as detailed and realistic as possible.

Results: Results indicated that the transversal rumble strips induced a speed reduction of 2.3 to 5.9 kph on the tangent before the curve. This speed reduction effect sustained over the experimental period of five days.

Conclusion and application: Taking the speed reduction effect into account, we can conclude that transversal rumble strips have a potential positive road safety effect because the reduced speed on the tangent provides more time to the drivers to make a good evaluation of the curve characteristics and environment and adapt their driving behavior in an appropriate way. Notwithstanding, we advise policy makers to make a good selection of potential dangerous curves to avoid excessive implementation of transversal rumble strips.

Highlights

- Transversal rumble strips (TRS) were implemented on tangent before dangerous curve
- Participants completed during 5 successive days the same driving simulator trip
- TRS induce speed reduction of 2.3 to 5.9 kph on the tangent
- Speed reduction effect sustain over the experimental period of 5 days
- Drivers have more time to adapt their driving behavior in an appropriate way

4.2.1 Introduction

Accident analyses show that curves are typically accident prone locations on the road network: accident rates are 1.5 to 4 times higher than on tangents (i.e., straight road sections) and 25 to 30% of all fatal accidents occur in curves. In addition, 60 to 70% of all fatal curve-related crashes are single-vehicle run-of-road accidents, whereas head-on collisions occur in 11% of the fatal accidents (Safetynet, 2009a; Torbic et al., 2004).

According to Charlton (2007), inappropriate speed monitoring, failure to maintain a proper lateral position and inability to meet increased attentional demands are the three main behavioral causative factors for accidents in curves. These factors are also related to an inadequate evaluation of the degree of hazard associated with a given curve (Staplin, Lococo, Byington, & Harkey, 2001).

Experimental research on road design and human factors showed that geometric curve properties often relate to these behavioral problems (Brenac, 1996; Khan et al., 2013; Safetynet, 2009a). Low curve radii (<200 m), inappropriate superelevation, too narrow road lanes and too long curve lengths are most frequently mentioned curve design elements which have adverse effects on road safety (Bonneson, Pratt, Miles, & Carlson, 2007; Khan et al., 2013; Safetynet, 2009a). In addition, a long preceding tangent length and a deviant sharp curve design of a single curve within a succession of gently designed curves are related to the extent to which the individual curve geometry fits within the surrounding road environment and showed to increase accident risks (R. Elvik et al., 2009; Findley, Hummer, Rasdorf, Zegeer, & Fowler, 2012; Safetynet, 2009a).

Several studies proposed a wide variety of pavement markings (i.e., directional arrows, centerline or shoulder rumble strips and (peripheral) transversal strips) and signs (i.e., (dynamic) warning signs, advisory speed signs and (chevron) alignment signs) in order to induce appropriate speed and lateral control in curves (Charlton, 2004, 2007; Comte & Jamson, 2000; Federal Highway Administration, 2012; Hallmark et al., 2014; Katz, 2004; McGee & Hanscom, 2006). Since this study focuses on pavement markings, and more specifically on transversal rumble strips, we briefly elaborate on the main working mechanism behind this perceptual countermeasure. Transversal rumble strips (TRS) consists of a sequence of transverse colored lines with a raised profile at decreasing distance apart in the travel direction (see Figure 56c). They manipulate the visual driving scene and the raised profile generates auditory and tactile feedback. These sensory inputs are meant to create an illusionary impression of increased motion which should result in a decrease in driving speed. Besides assisting drivers in more optimally speed monitoring, TRS have an important alerting function (Godley, 1999; Merat & Jamson, 2013).

Although a wide variety of patterns, colors and spacings are implemented, several field and driving simulator studies have demonstrated the potential speed reduction effect of transversal (rumble) strips in combination with intersections (Godley, 1999; S. Jamson & Lai, 2011; Montella et al., 2011), rural-urban transitions (S. Jamson et al., 2010), work zones (Bryden, Corkran, Hubbs, Chandra, & Jeannotte, 2013; Meyer, 2004) and curves (Ariën et al., 2016; Comte & Jamson, 2000; Gates et al., 2008; Godley, 1999; Montella, Galante, Mauriello, & Pariota, 2015a). Elliot, McColl and Kennedy (2003; in Charlton & Baas, 2006) reported localized speed reductions between no effect up to 9,6 kph for transverse groupings of rumble strips. Godley (1999) established speed reductions between 8 and 11 kph near intersections and curves equipped with transverse lines. These results are in line with the speed reduction effects near intersections reported by Montella et al. (2011) (i.e., between 3 and 15 kph). Nevertheless, Rossi et al. (2013) found only moderate speed reductions for optical transversal speed bars near roundabouts (i.e., up to 2 kph). According to Elvik, Høye, Vaa and Sørensen (2009), rumble strips have a positive effect on road safety near junctions: injury accidents are reduced by 33% and the number of property-damage-only accidents decreased with 25%. Although these auspicious results, there is some doubt about the durability (both in time and distance) of the speed reduction effects (Comte & Jamson, 2000; Gates et al., 2008). The literature review of Martens et al. (1997) described that some experiments found that effects remained stable after a year (Zaidel et al., 1986), while others report that the effects lessen after some weeks or days (Maroney & Dewar, 1987).

Related to these inconclusive effects under repeated exposure (i.e., effect over time), Ariën et al. (2014) (paragraph 3.2) performed a literature review concerning the potential influence of novelty effects related to traffic calming measures on driving simulator performance data as described by Jamson and Lai (2010). Besides the various advantages related to driving simulator research (e.g., total control over various driving conditions, safe, cost efficient, collection of a variety of continuous high rate driving performance data), simulator validation, participant self-selection, simulator sickness and novelty effects should be taken into account (S. Jamson et al., 2010; L. Nilsson, 1993; Rudin-Brown et al., 2009). These novelty effects can be related to the simulator system itself, but can also apply for the specific treatment being tested (for instance traffic calming measures or perceptual countermeasures). Ariën et al. (2014) (paragraph 3.2) subdivided driving simulator experiments during which subjects were repeatedly exposed to an identical treatment into two groups: (1) participants were exposed several times to the same treatment during one single simulator session (e.g., Brown, 2001; S. Jamson et al., 2010; Lewis-Evans & Charlton, 2006; Rossi et al., 2013a, 2013b) and (2) participants were exposed several times to the same treatment during multiple simulator sessions spread over different days (e.g., Åkerstedt et al., 2010; Charlton & Starkey, 2011; Domeyer et al., 2013; I. M. Harms & Brookhuis, 2016; Jenssen et al., 2007; Lenné et al., 1997; Manser & Creaser, 2011; Martens & Fox, 2007).

However, the literature available is rather scarce when it comes to examining the impact of technological and/or infrastructural treatments under conditions of repeated exposure on driving behavior. The studies of Jamson and Lai (2011) and Rossi et al. (2013a, 2013b) are the only references we are knowledgeable of which test the impact of infrastructural perceptual countermeasures under repeated exposure specifically. In both studies subjects participated during one single simulator session during which each participant passed four (S. Jamson & Lai, 2011) and ten times (Rossi et al., 2013a, 2013b) the same infrastructural measurements. Rossi et al. (2013a, 2013b) averaged the driving performance parameters over the ten trials and did not analyze the effect of the repeated exposure. Jamson and Lai (2011), on the other hand, observed three types of behavioral effects within their range of tested treatments: initial behavior shows a stronger / weaker than future behavior and future behavior can be predicted by initial behavior. Based on this literature review, the main objectives and more specific research questions are formulated.

4.2.2 Objectives and research questions

This study investigates the impact of transversal rumble strips (TRS) located on the tangent before two dangerous curves on the driving behavior of a sample of participants who will be repeatedly exposed to this specific perceptual countermeasure. The main research questions are formulated as follows:

1. Do TRS nearby dangerous curves influence mean speed?
2. How far in distance along the road does the influence of TRS nearby dangerous curves reach?
3. Does the effect of TRS nearby dangerous curves change when the same subjects are repeatedly exposed?

4.2.3 Methodology

A. Participants

Participants were recruited via e-mail at Hasselt University. Twelve of the twenty-nine volunteers were excluded: three participants suffered from simulator sickness, six participants could not complete the experimental period of five successive days due to technical problems and two participants were identified as outlier. A participant was defined as an outlier when he/she drove faster or slower than three inter-quartile distances from the group's mean during 25% of the analysis section. Thus, the remaining sample consists of 18 participants (8 men; mean age: 27.7; SD age: 11.5). All participants had (corrected to) normal vision and gave informed consent. Gender and age were not taken into account as between-subject factors in the statistical analysis.

B. Apparatus

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-base (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual and auditory feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images and depiction of the speedometer. Three projectors offer a resolution of 1024 x 768 pixels and a 60 Hz refresh rate. The sounds of traffic in the environment and of the participant's car were presented. The data, which was collected at a 60 Hz frame rate, was interpolated to a 1 m distance interval before starting the data analysis.

C. Simulation scenario

During the 17 km driving scenario four curves, alternated with filler pieces (see Figure 56a), were presented to the participants. The curves were programmed according to geo-specific database modelling method. Yan et al. (2008b) defined this method as "replicating a real-world driving environment in a simulated virtual world" and is to be differentiated from the fictive driving scenarios. The real-world curves which were replicated in this driving simulator scenario were picked from the existing Flemish road network by means of extensive selection procedure using for instance the official Belgian accident database (Federal Government Statistics Belgium, n.d.) and detailed accident maneuver diagrams. The detailed selection procedure is described in Ariën et al. (2016) (paragraph 4.1.3) and resulted in two dangerous left-oriented compound curves (i.e., combination of different curve radii in one curve) which were both preceded by a long tangent. Table 16 shows more detailed information on the curve characteristics.

Table 16 Curve properties of Location A and B

	Loc A	***Loc B***		***Loc A***	***Loc B***		***Loc A***	***Loc B***
Radius 1	170m	169m	Length 1	17m	51m	Total curve length	130m	116m
Radius 2	94m	92m	Length 2	29m	19m	Speed limit	90kph	70kph
Radius 3	161m	97m	Length 3	46m	21m	Road lane width	3.2m	2.8m
Radius 4	219m	688m	Length 4	38m	25m	Bicycle facilities	Yes	No

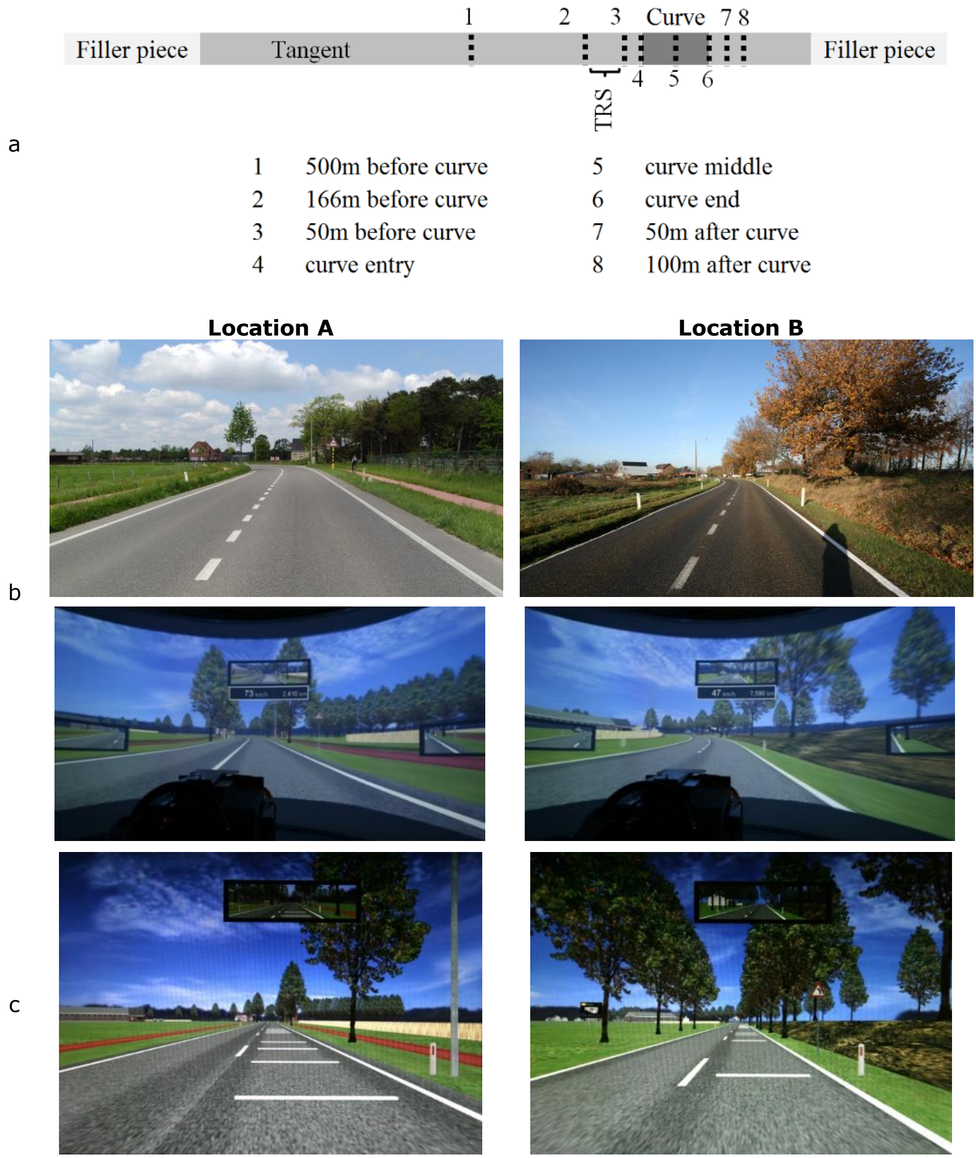


Figure 56 (a) Scenario overview; (b) real world versus simulator images nearby curves at location A (left) and B (right); (c) simulator images of TRS at location A (left) and B (right)

Two of the four presented curves were located at location A, while the other two curves had the road and environmental characteristics of location B. At both locations, one curve was equipped with TRS (see Figure 56c), while no additional countermeasures were implemented at the other two curves. TRS were located between 155 and 66 m before the curve entrance (Vanduyver & Depestele, 2002, p. 303) and each passage over a strip was accompanied by both auditory and tactile feedback provided by the sound equipment and the steering wheel of the driving simulator. The impression of increased motion is generated optically by means of the sequence of transverse lines at decreasing distances apart in the travel direction (see Figure 47).

Statistical analyses were performed on the tangent (1200 m) followed by the compound curve and ended again with a tangent (300 to 375 m). The filler pieces, which connected these curve sections, were meant to provide some variation in the driving scenario and consisted of road segments with a variety of speed limits (e.g., 30, 50, 70 and 90 kph), surrounding environment (e.g., rural or urban) and daily changing interactions with other road users. The last 700 m before the first analysis point (i.e., 500 m before the curve entry) was standardized in order to prevent interference from these small day-to-day variations. Weather conditions were sunny and dry.

D. Procedure

Participants agreed to take part for a period of five consecutive weekdays. On the first day, participants were asked to fill out their personal data (e.g., gender, date of birth) and to give their informed consent. The general introduction in the driving simulator was followed by two practice scenarios ((1) 4 km rural road with some slight curves and (2) 7 km with successively a motorway, a 70 kph rural road with a dangerous curve and an urban area) in order to get acquainted with the simulator. During the subsequent test trip of 17 km participants passed four dangerous curves (i.e., two curves at location A and two curves at location B and at each location once with TRS and once without TRS) in a counterbalanced order. The order of the four curves (location and TRS present or absent) did not change during the whole experiment for a particular participant because we were specifically interested in the driving behavior of participants who were repeatedly exposed to the TRS in the same configuration. The guidance instructions were provided by a GPS voice. Subjects were instructed to apply the traffic laws as they would (or would not) do in reality and to drive as they normally would in their own car.

E. Data collection and analysis

The main purpose of the TRS under investigation is to improve road safety. Because of the positive relationship between driving speed, crash risk and severity (Safetynet, 2009b), mean speed is analyzed at eight analysis point along the driving scenario (see Figure 56a).

A 2 (marking: no TRS, TRS) × 5 (day) × 8 (points) within-subjects analysis of variance (ANOVA) was conducted on mean speed for each location separately. Based on Kolomgorov-Smirnov tests of normality and Mauchly's test of sphericity we corrected for deviation from normality (Bonferroni correction) and sphericity (Greenhouse-Geisser epsilon correction). *P*-value was set at 0.05 to determine statistical significance. F- and partial eta squared values are mentioned.

4.2.4 Results

Table 17 ANOVA statistics for location A and B (significant p-values are indicated in bold)

Greenhouse-Geisser	F (dfs)	**Location A** *p*	Parial eta squared
Marking	5.9 (1, 17)	**0.027**	0.257
Day	1.0 (3, 51)	0.593	0.036
Point	121.5 (2, 39)	**<0.001**	0.877
Marking × Day	1.5 (3, 48))	0.228	0.081
Marking × Point	5.8 (2, 36)	**0.006**	0.255
Day × Point	3.3 (8, 129)	**0.002**	0.164
Marking × Day × Point	1.0 (7, 124)	0.415	0.057

Greenhouse-Geisser	F (dfs)	**Location B** *p*	Parial eta squared
Marking	4.6 (1, 17)	**0.047**	0.212
Day	8.1 (3, 45)	**<0.001**	0.322
Point	43.1 (2, 38)	**<0.001**	0.717
Marking × Day	1.4 (3, 47)	0.244	0.078
Marking × Point	3.6 (3, 48)	**0.023**	0.174
Day × Point	3.5 (7, 115)	**0.002**	0.171
Marking × Day × Point	1.8 (5, 93)	0.106	0.098

A. Location A

The daily values for mean speed on the 8 points separated for the condition without and with TRS are shown in Figure 57 and Figure 58 respectively. At 500 m before the curve mean speed was highest and close to the speed limit of 90 kph. During the first four days, participants decelerated to a minimal mean speed near the curve middle. On the fifth day, mean speed was already minimal at the curve entry. Once participants passed the curve middle, they started to accelerate again at a continuous level, but there is some indication that they accelerated more as the days progressed. Overall, mean speed seems to be lower at 166 m and 50 m before the curve entry when TRS were present. In addition, at the curve entry mean speed was very constant during the whole experimental period when TRS was present, compared to the slightly higher mean speeds during the first two days of the experiment and the larger spread over the different days when TRS was absent.

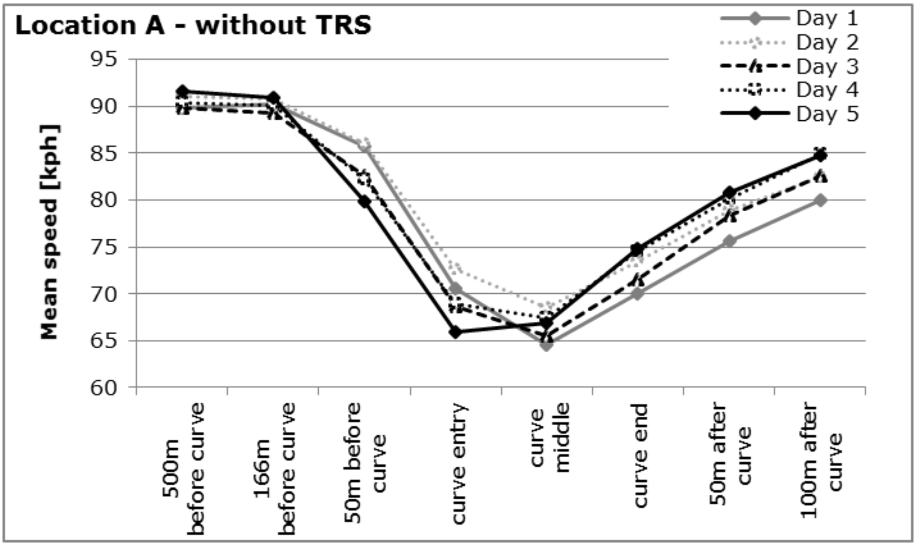


Figure 57 Mean speed as a function of Marking × Day × Point: TRS absent at location A (TRS were located between 150 and 66 m before the curve entry)

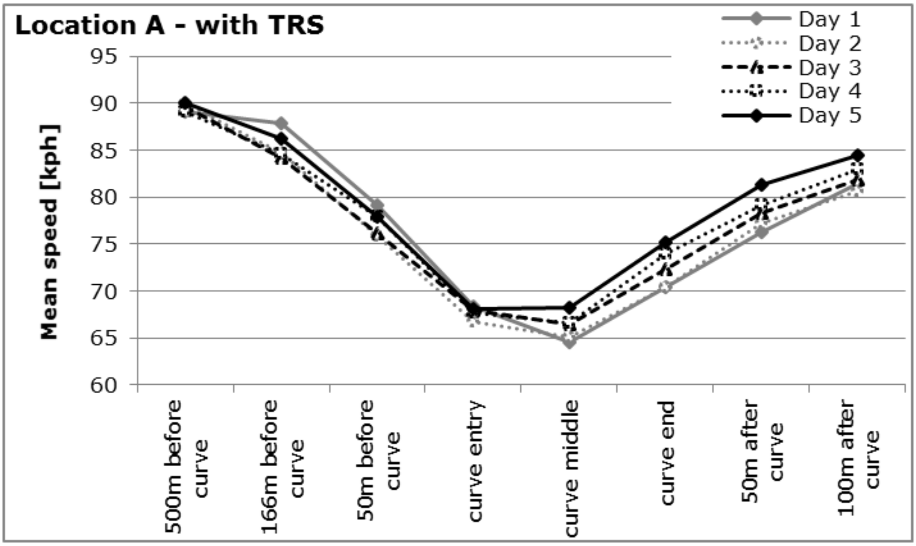


Figure 58 Mean speed as a function of Marking × Day × Point: TRS present at location A (TRS were located between 150 and 66 m before the curve entry)

The ANOVA for location A showed a significant main effect of *Marking* and *Point*. In addition, there was a significant interaction effect of *Marking* × *Point* and *Day* × *Point*. Since the combination of the factors *Marking* and *Day* were not significant in a two- or three-way interaction, we can conclude from the significant interaction of *Marking* × *Point* that mean speed varied across the different points in function of the presence or absence of TRS, but not in function of the day. This means that the effects generated by the TRS on a certain day did not significantly differ from the other four days. Figure 59 shows the mean speed values on the 8 points, separated for the condition with or without TRS but irrespective of the day. Post-hoc analysis for the interaction effect of *Marking* × *Point* showed that mean speed was 4.7 to 5.9 kph lower at respectively 166 m ($F_{(1, 17)} = 8.4$, $p = 0.010$, $\eta_p^2 = 0.330$) and 50 m ($F_{(1, 17)} = 12.6$, $p = 0.002$, $\eta_p^2 = 0.426$) before the curve entry when TRS was present. At the other 6 points, there were no significant differences in mean speed between the condition with or without TRS.

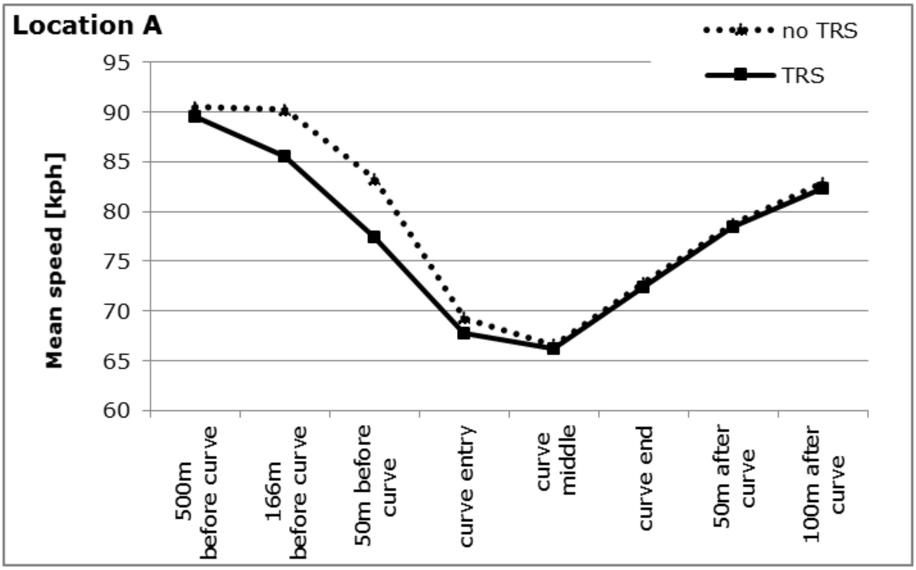


Figure 59 Mean speed for the interaction of Marking × Point at location A (TRS were located between 150 and 66 m before the curve entry)

Mean speed values on the 8 point, separated for the 5 days but irrespective of the presence or absence of TRS are shown in Figure 60. Post-hoc analysis for *Day* × *Point* showed that some mean speed values significantly varied across the different points on the different days. Interestingly, during the first four days minimal mean speeds were reached at the curve middle, while on the last day participants reached a minimal speed already at the curve entry and continued this speed until the curve middle. It is however important to note that there was no significant difference in mean speed between the curve entry and middle at day 4. Although Figure 57, Figure 58 and Figure 60 gave some indication that mean speed increased at the curve end and at 50 and 100 m after the curve end as the days progressed, this was not confirmed by the pairewise comparisons.

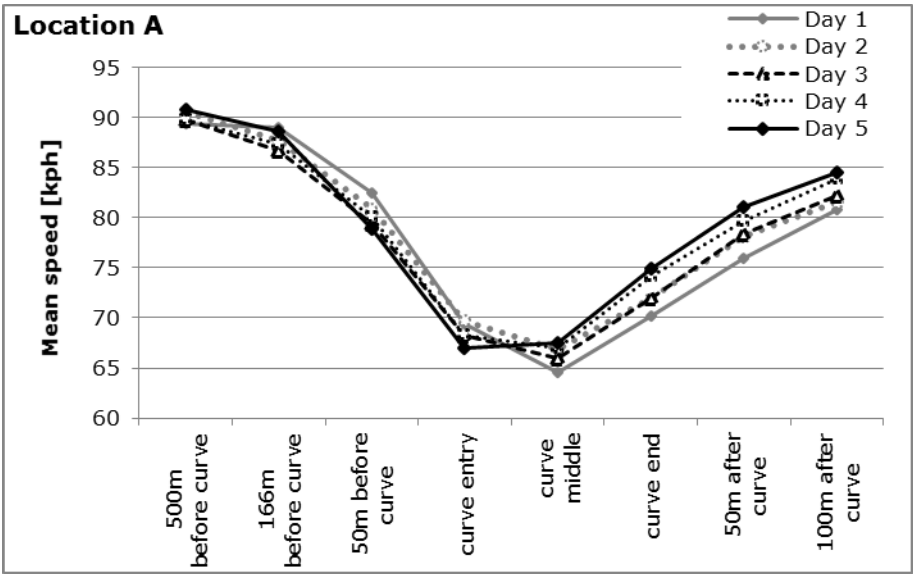


Figure 60 Mean speed for the interaction of Day × Point at location A (TRS were located between 150 and 66 m before the curve entry)

B. Location B

Figure 61 and Figure 62 show the daily mean speed values for location B on the 8 points, respectively for the condition (a) without and (b) with TRS. Starting from a mean speed slightly about the speed limit of 70 kph at 500 m before the curve, participants decelerated to a minimal speed at the curve middle during the five experimental days when TRS was absent. When TRS was present, the same deceleration behavior was present during the first three days, but at day 4 and 5 participants reached their minimal speed already at the curve entry. In addition, both in the condition with and without TRS there seem to be an indication that mean speed increased as the days passed by. Overall, mean speed seems to be lower at 166 m and 50 m before the curve entry when TRS were present. At the curve entry, there seems to be some indication that mean speed was lower during the first two days when TRS was present.

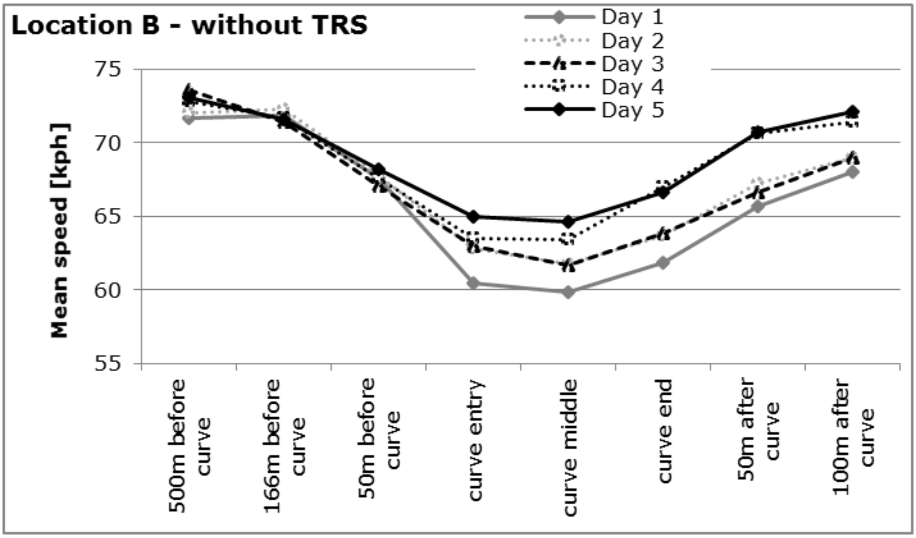


Figure 61 Mean speed as a function of Marking × Day × Point: TRS absent at location B (TRS were located between 150 and 66 m before the curve entry)

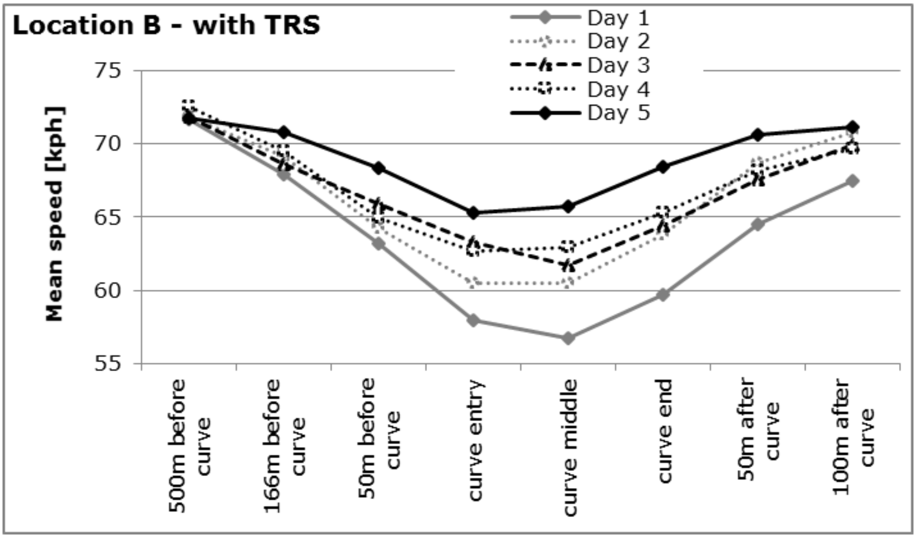


Figure 62 Mean speed as a function of Marking × Day × Point: TRS present at location B (TRS were located between 150 and 66 m before the curve entry)

The ANOVA for location B showed comparable significant main and interaction effects as at location A, but the main effect of *Days* was also significant at location B. Since the interaction between *Marking* and *Day* or between the three factors was not significant, the interaction effect of *Marking* × *Point* indicated that mean speed might have varied across the different points in function of the presence or absence of TRS, but this interaction was irrespective of the day. This means that the effects generated by the TRS on a certain day did not significantly differ from the other four days.

Mean speed values at the 8 points separated for the condition with and without TRS, but irrespective of the day are shown in Figure 63. Post-hoc analysis for *Marking* × *Point* showed that mean speed was 2.6 to 2.3 kph lower at respectively 166 m ($F_{(1, 17)}$ = 12.0, p = 0.003, η_p^2 = 0.414) and 50 m ($F_{(1, 17)}$ = 8.2, p = 0.011, η_p^2 = 0.325) before the curve entry when TRS was present. In addition, TRS generated a marginally significant speed reduction of 1.0 kph at the curve entry ($F_{(1, 17)}$ = 3.5, p = 0.077, η_p^2 = 0.173).

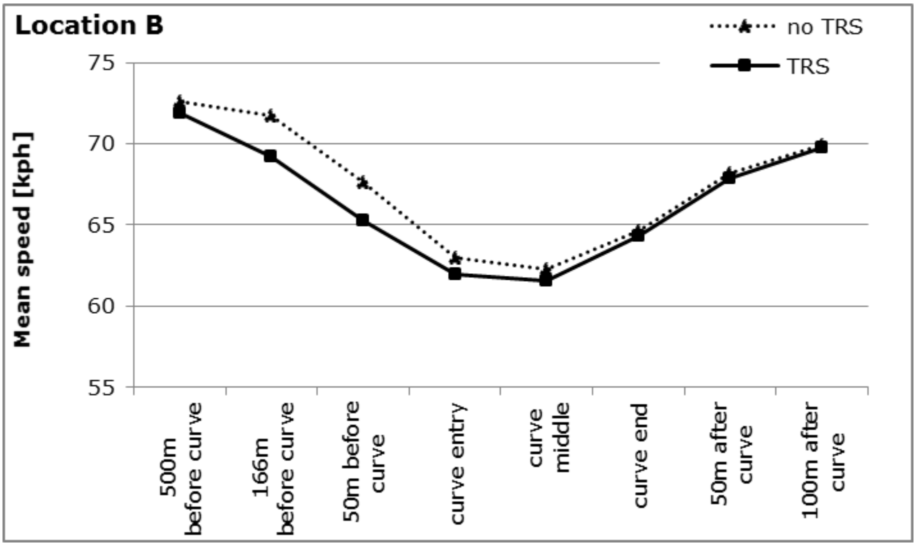


Figure 63 Mean speed for the interaction of Marking × Point at location B (TRS were located between 150 and 66 m before the curve entry)

Figure 64 shows the mean speed values at the 8 points, separated for the 5 days but irrespective of the presence or absence of TRS. Although there were significant speed differences between the curve entry and middle during the total experimental period, mean speeds were slightly (but not significant) lower at the curve middle during the first three days. On the two last days, minimal speed was reached at the curve entry. Comparing the mean speed values at each point between the different days shows that mean speed was significant lower at the first two days compared to the last day from the curve entry until the curve end. In addition, mean speed was also significant lower from the curve end until 100 m after the curve at the first day compared to day 4 and 5. Finally, mean speed at day 3 was significant lower than at day 5 at 50 m after the curve.

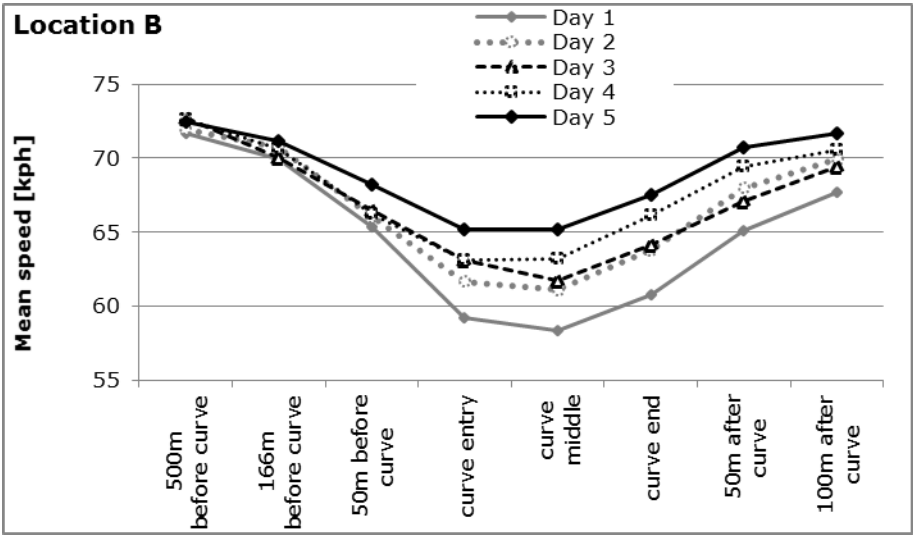


Figure 64 Mean speed for the interaction of Day × Point at location B (TRS were located between 150 and 66 m before the curve entry)

4.2.5 Discussion

In this driving simulator study we analyzed mean speed to find out (1) whether TRS located on the tangent before dangerous curves influences mean speed; (2) how far the influence reaches and (3) whether the effect would change when the same participant is repeatedly exposed during a period of 5 successive days. In addition, we try to relate the established results with the geometric curve characteristics of the two dangerous curves under investigation.

Besides some main effects, the ANOVA showed a significant interaction effect of *Marking* × *Point* and *Day* × *Point* for both location A and B. The absence of a significant interaction between the factors *Marking* and *Day* or between the three factors *Marking*, *Day* and *Point* reveal that the potential influence of TRS on mean speed is independent of the day. This means that the effects generated by TRS on a certain day were not significant different from the other four days.

During the five successive days of the experiment and at both curve locations, TRS generated a significant speed reduction on the tangent in the direct vicinity of the TRS, more specifically at 166 and 50 m before the curve (TRS was located between 150 and 66 m before the curve). At location A, significant speed reductions between 4.7 and 5.9 kph were measured. The size of the speed reduction effect of the TRS at location B was smaller (i.e., 2.3 to 2.6 kph), but there was also a marginally significant speed reduction effect at the curve entry of 1.0 kph. These speed reductions are in line with the results of for instance Elliot et al. (2003), Montella et al. (2011; 2015a) and Rossi et al. (2013b). According to Elvik's power model for rural roads (R. Elvik, 2009, p. 58), speed reductions of that size might decrease fatal accidents and injury accidents on the tangent at location A up to 35% and 12% respectively and up to 16% and 6% at location B.

Several studies established that drivers start to explore curves between 100 m and 30 m before the curve entry (Milleville-Pennel et al., 2007; Tsimhoni & Green, 1999). The lower driving speed on a tangent equipped with TRS gives drivers thus more time to satisfy the increased need for visual information on curved roads, to make an adequate evaluation of the degree of risk and to meet increased attentional demands associated with the curve. In addition, due to their lower speed on the tangent, drivers are less forced to suddenly adapt their driving behavior just before they enter the curve or along the curve itself. This is an important issue because accidents occur primarily at both the curve entry or the curve end (PIARC, 2003).

The results of the interaction of *Day* × *Point* showed that a minimal mean speed was reached at the curve middle at the first three days and at the curve entry at the last two days. These results are somewhat in line with Mintsis (1988) who observed lowest speed in the middle of the curve and Taragin (1954) who suggested that drivers adjust their speed before entering a curve and continue at a contact speed throughout the curve. Another element related to this interaction effect is the (indication of an) increase in mean speed beginning at the curve entry as the days pass by. This evolution over the days might be related to Wilde's theory of risk homeostasis (Milleville-Pennel et al., 2007) or Weller's driving behavior model (Weller et al., 2008) in which drivers adjust their driving behavior as a result of an appraisal of the perceived risks with an acceptable risk threshold. During the first days, participants seem to 'overestimate' the perceived risk of the curves and lower their speed. However, the successive exposure during the following days might adjust their risk perception and participants feel confident to increase their mean speed which does not benefit road safety.

A comparison of the V_{85} speed differential between the tangent (166 m before the curve) and the curve entry show a larger reduction of V_{85} at location A (12 kph) compared to location B (5 kph). According to Lamm et al. (1999) the latter curve has a good design quality, whereas the design quality of curve A is acceptable. In addition, Anderson et al. (in PIARC, 2003) established that the accident rate at a curve section with a speed differential of 10 kph to 20 kph is twice as high as a curve with a speed differential of less than 10 kph. The established differences in driving behavior at location A and B can be attributed to the differences in their geometric design characteristics and the different curve radii and curve lengths of the individual curve segments of the compound curves (see Table 16). Odhams and Cole (2004) found for instance a positive relationship between speed choice and both lane width and curve radius. The lower speed limit of 70 kph, the absence of bicycle facilities and the smaller lane width at location B might be the main reasons why mean speed at location B was lower than at location A.

4.2.6 Limitations and future research

The reporting of results of driving simulator studies often goes together with discussions about external validity. Although moving base simulators generated a greater degree of realism (Bella, 2009), several studies showed indications that fixed-base driving simulators can examine geometric design issues in a perfectly adequate way (e.g., Bella, 2007, 2008; Benedetto, Calvi, & Messina, 2012; Calvi et al., 2012; Charlton, 2004; Federal Highway Administration, 2007). In addition, the 180° seamless curved screen used in this study satisfies the prescribed minimum field of view of 120° in order to make correct estimation of longitudinal speed (Kemeny & Panerai, 2003).

Future research on TRS can focus on additional driving parameters related to longitudinal and lateral speed (e.g. acceleration/deceleration or lateral position) or on different geometric design configurations to improve road safety nearby dangerous curves. Although we tried to anticipate the potential influence of novelty effects of TRS on mean speed by this quite unique experimental setup (besides the studies of Ariën, Brijs, Brijs, et al., 2014; S. Jamson & Lai, 2011; Rossi et al., 2013a, 2013b) where participants were repeatedly exposed during 5 successive days, we are unable to pronounce upon the long term effect of these TRS as in a before-after field experiment. Future research can thus focus on longer term naturalistic driving studies and a before-after field experiment.

4.2.7 Conclusion and policy recommendations

The paper has investigated the effect of transversal rumble strips (TRS) located near dangerous curves on mean speed of a sample of participants who were repeatedly exposed to this specific perceptual countermeasure. The driving simulator study has established that TRS generated a significant reduction of mean speed (i.e., between 2.3 kph and 5.9 kph) on the tangent proceeding to the curve and that these effects on mean speed are irrespective of the day. The speed reduction effect sustained thus over the five-day experiment period. Although the speed reduction effect did not proceed until the curve entry and further along the curve, the lower speed on the tangent gives drivers more time to make an adequate evaluation of the degree of risk with the curve and to adapt their driving behavior in an appropriate way. This is in line with the study of Lee, McGehee, Brown and Reyes (2002) showing that early warnings (TRS were located between 155 and 66 m before the curve entry) might be helpful for a quicker reaction. Besides this potential positive effect on mean speed, TRS work also as an alerting device (Merat & Jamson, 2013). Despite these favorable effects, some studies warn for the produced noise when a vehicle passes by the TRS (Dewar & Olson, 2007; Martens et al., 1997). Based on these results, we can conclude that TRS is a low-cost perceptual countermeasure that has the potential to improve road safety near dangerous curves. Notwithstanding, we advise policy makers to make a good selection of potential dangerous curves to avoid excessive implementation of transversal rumble strips.

Chapter 5

CONCLUSIONS, METHODOLOGICAL ISSUES AND FUTURE CHALLENGES

5.1 OVERVIEW OF THE MAIN RESULTS OF THE DRIVING SIMULATOR EXPERIMENTS

The main purpose of this thesis was to get more insight in the effect in distance and time of traffic calming measures (TCM) near road transitions and discontinuities. Rural-to-urban transition and tangent-to-curve discontinuity both require an adaptation of the drivers' behavior. In Flanders, the speed limit on a rural road is 70 kph (in some exceptions 90 kph) while the maximum speed in an urban area is 50 kph. Besides this important speed reduction, drivers have to increase their attention level in the urban area as more and complex interactions with a variety of road users are required. Besides a safe driving speed, a stable lateral position and a smooth acceleration and deceleration improve road safety (Marchesini & Weijermars, 2010; Rosey et al., 2008). Finally, Charlton (2007) proposed three main causative factors for accidents in curves, i.e., inappropriate speed monitoring, failure to maintain proper lateral position, and inability to meet increased attentional demand.

Three driving simulator studies were performed to investigate the effect of gate constructions and different messages on digital information displays (DID) near the transition from a rural to an urban area. In addition, two experiments investigated the effect of transversal rumble strips (TRS) and a herringbone pattern (HP) which were implemented on the tangent and in a dangerous curve respectively. The effects of gates and TRS were also examined in a longitudinal experiment where drivers participated during five successive days in the driving simulator experiment. The main results of these studies are summarized in Table 18 and described below. In addition, Table 18 gives an overview of the key characteristics of each driving simulator study. More detailed information about the methodological design and detailed results can be found in the separate chapters.

The obtained results can support road safety authorities and road designers in their design and decision making process as the results provide information about the effects in distance and time on driving behavior and road safety. In sum, these results can help to improve road design in the context of a Safe System Approach. Based on these results practical implications and policy recommendations are described in paragraph 5.2. Furthermore, a reflection about the application of a driving simulator to the evaluation of geometric road design is offered in paragraph 5.3. Finally, paragraph 5.4 elaborates on future research and challenges with respect to the implementation of traffic calming measures in a self-explaining road network.

Table 18 Overview of the main results of the five driving simulator studies

§	TCM	n	Methodological design	Main effects	Distance
3.1	Gates at the rural-to-urban transition	46	Cross sectional design Curves (present, absent) x Gates (present, absent) x Analysis zone within-subjects MANOVA	Mean v: no gate > gate (3 kph) SDAD: no gate < gate SDLP: no gate < gate	*0 m = entrance* -97 m … +97 m -97 m … +282 m -97 m … +97 m
3.2	Gates at the rural-to-urban transition	17	Longitudinal design Gates (present, absent) x Day (5 successive days) x Analysis zone within-subjects MANOVA	<u>*During 5 successive days*</u> Mean v: no gate > gate (1.2 - 4 kph) no gate < gate (0.8 kph) SDAD: no influence of gate SDLP: no influence of gate	*0 m = entrance* -200 m … +100 m +100 m … +200 m
3.3	Digital information display just after the rural-to-urban transition	66	Cross sectional design DID (baseline, smiley, too fast, speed enforcement) x Analysis zone mixed-subjects MANOVA at two locations	Mean v: *Location A* baseline > speed enfor. (2.0 - 3.2 kph) smiley > speed enfor. (2.1 - 2.2 kph) too fast > speed enfor. (1.9 - 2.0 kph) *Location B* baseline > 3 DID messages smiley (1.9 - 2.8 kph) too fast (2.3 - 3.1 kph) speed enfor. (2.3 - 3.2 kph) Mean dec: *Location A* no influence of DID *Location B* baseline < DID baseline < too fast & speed enfor. smiley < speed enfor.	*0 m = DID* -25 m … +175 m +25 m … +100 m 0 m … +75 m -50 m … +75 m -25 m … +100 m -25 m … +100 m -50 m … -25 m -25 m … 0 m -25 m … 0 m

§	TCM	n	Methodological design	Main effects	Distance
4.1	Transversal rumble strips on the tangent before the curve & Herringbone pattern along the curve	32	Cross sectional design Curve direction (left, right) x Marking (baseline, TRS, HP) x Analysis point within-subjects MANOVA at two locations	Mean v: *Location A* baseline > TRS (8.9 - 9.8 kph) HP > TRS (6.9 - 10.1 kph) baseline > HP (2.5 - 3.5 kph) *Location B* baseline > TRS (2.3 - 5.3 kph) baseline > HP (2.2 - 2.8 kph) HP > TRS (6.2 kph) Mean dec: *Location A* baseline & HP < TRS baseline & HP > TRS *Location B* baseline & HP < TRS Mean LP: *Location A* no influence of TRS or HP *Location B* left curve: closer to lane edge in control condition compared to TRS & HP	*0 m = curve entry* -166 m … -50 m -166 m … -50 m 0 m … ½ curve & ¾ curve -166 m … ½ curve 0 m … curve end -166 m -166 m -50 m … 0 m -50 m Aggregated over 10 points
4.2	Transversal rumble strips on the tangent before the curve	18	Longitudinal design Marking (baseline, TRS) x Day (5 successive days) x Analysis point within-subjects ANOVA at two locations	<u>*During 5 successive days*</u> Mean v: *Location A* baseline > TRS (4.7 - 5.9 kph) *Location B* baseline > TRS (1.0 - 2.6 kph)	*0 m = curve entry* -166 m … -50 m -166 m … 0 m

5.1.1 Longitudinal control

The two driving simulator studies (Ariën et al., 2013a; Ariën, Brijs, Brijs, et al., 2014) (paragraph 3.1 and 3.2) investigating the influence of a **gate construction**, located at the entrance between a rural and urban area, showed a significant speed reduction between -1.2 and -4.0 kph. The longitudinal analysis showed that this speed reduction effect sustained during the five successive days of the research. Although a significant speed reduction was found, the effect was limited to the direct vicinity of the gate (i.e., from 200 m before until 100 m after the entrance). Even though participants were inclined to accelerate again once passed by this gate, they always kept driving at an appropriate speed, i.e., close to the speed limit of 50 kph. Finally, drivers performed this speed reduction rather smoothly as the standard deviation of acceleration/deceleration (SDAD) was only slightly influenced by the presence of the gate.

During a third driving simulator experiment (Ariën, Cornu, et al., 2014) (paragraph 3.3) participants were exposed to three different messages on a **digital information display** (DID) which was located after the rural-to-urban transition. Although the results were not exactly the same at both locations under investigation, the "Speed enforcement" message was most effective in reducing the driving speed (i.e., -2.0 to -3.2 kph from 25 m before until 175 m after the DID), followed by the "Too fast" message (-2.3 to -3.1 kph from 25 m before to 100 m after the DID) and the Smiley logo (-1.9 to -2.8 kph from 50 m before until 75 m after the DID) compared to the baseline condition. This implies that a deterrence strategy, where drivers are confronted with the (financial) risk of receiving a fine, is more effective in reducing speed compared to the social approval/ disapproval messages. In addition, the post-experiment survey showed that messages indicating a speed enforcement or a fine were considered by participants as the most effective. With respect to mean acc/dec, the strongest deceleration maneuver was established during the last 50 m before the DID. The deceleration rate around the DID in this study is not higher than -0.20 m/s². This can be seen as a safe deceleration rate in light of deceleration values recommended by other studies: -0.85 m/s² (PIARC, 2003), -3.40 m/s² (PIARC, 2003) or -4.40 m/s² (Hu & Donnell, 2010). It is crucial that deceleration values are below these recommended values to obtain a safe traffic environment. Too high deceleration rates can lead to rear-end collisions and disturbances in the traffic flow.

Finally, the discontinuity from a tangent to a dangerous curve was investigated at two locations. The fourth driving simulator study (Ariën et al., 2016) (paragraph 4.1) compared two perceptual pavement markings, i.e., transversal rumble strips located at the tangent before the curve and **herringbone pattern** (HP) located along the curve. The latter pavement marking reduced driving speed from the curve entry until the curve end between -2.2 and -3.5 kph compared to the baseline condition. The maximum deceleration in the HP condition was located at

50 m before the curve. In addition, the threshold of a deceleration of more than -0.85 m/s² was exceeded at location A indicating an increased risk for rear-end collisions or disturbances in the traffic flow. The **transversal rumble strips** (TRS) were the most effective on the tangent and the resulting lower driving speed gave participants more time to obtain the right expectation about the upcoming curve. At location A speed reductions between -8.9 and -9.8 kph were measured between 166 and 50 m before the curve in the cross-sectional experiment. A speed reduction between -4.7 and -5.9 kph remained during the experimental period of the five days in the longitudinal study (Ariën, Brijs, Vanroelen, et al., 2014) (paragraph 4.2). The TRS resulted in speed reductions between -2.3 and -5.3 kph between 166 m before the curve and the curve middle at location B. Speed reductions between -1.0 and -2.6 kph were measured between 166 m before the curve and the curve entry under repeated exposure. Although these speed reductions were often larger than the speed reductions induced by the HP, the deceleration maneuver was smoother (max mean dec: -0.786 m/s²) compared to the baseline condition and started already at 166 m before the curve. The differences between location A and B can be related to the different design characteristics of both curves (i.e., curve radii, curve length, lane width, presence of bicycle lanes etc.) and the speed limits. The comparison of the maximum absolute speed reduction at the two curves under investigation showed a poor design quality for location A (speed difference = 32 kph) and a fair quality at location B (speed difference = 17 kph).

In conclusion, all the traffic calming measures under investigation showed a significant local speed reduction compared to the baseline condition. These speed reductions typically ranged from 2 to 4 kph. In addition, the TRS showed speed reductions up to 9.8 kph on the tangent before a dangerous curve. In general, all speed reductions were limited to the direct vicinity of the traffic calming measure with a maximum influence range of 200 m before until 200 m after the TCM. Furthermore, the gates and the TCM have the potential to improve road safety under repeated exposure. Finally, these speed reductions are accompanied by an increase in the SDAD showing more variations in speed and an increase in mean deceleration compared to the baseline condition. However, the mean deceleration level remained at a safe level above the standard of -0.85 m/s². In addition, the TRS induced a smoother deceleration maneuver on the tangent before the curve compared to the stronger deceleration in the baseline condition.

5.1.2 Lateral control

Besides the longitudinal control, managing the vehicle's horizontal position within the driving lane is also an important factor in road safety. The cross-sectional experiment (Ariën et al., 2013a) (paragraph 3.1) revealed a higher SDLP within the direct vicinity of the **gate construction** (i.e., between 97 m before and 97 m after the entrance). This effect however was not present in the longitudinal experiment (Ariën, Brijs, Brijs, et al., 2014) (paragraph 3.2). Furthermore, the influence of the **TRS** and **HP** was rather limited (Ariën et al., 2016) (paragraph 4.1). The effect of **DID** on lateral control was not investigated in this thesis.

In sum, the effects of the traffic calming measures under investigation on lateral control are too small to expect road safety problems.

5.2 POLICY RECOMMENDATIONS WITH RESPECT TO TRAFFIC CALMING MEASURES

Based on the results of the different driving simulator experiments, several recommendations can be proposed which can support road agencies and road designers to make their design safer within the Safe System Approach. The fact that the various TCMs, studied apart and at specific transitions and discontinuities, result in speed reductions which are limited to the direct vicinity of the TCM has some implications for the design at a macro, meso and micro level.

The **macro level** concerns the selection of the specific location within the road network to implement a traffic calming measure. Within the context of the decision to implement a gate construction at the rural-to-urban transition, this will depend on contextual factors such as whether the road serves a traffic-, rather than a residential function. When the entrance of an urban area is surrounded by residential functions such as a school, a hospital or shops, a gate construction has the potential to lower speed and improve road safety nearby the entrance. Concerning the implementation of TRS or HP near tangent-to-curve discontinuities, we advise road agencies to make a good selection of potential dangerous curves to avoid excessive implementation of these perceptual pavement markings. This selection can be based on research related to the selection of black spots and network screening (e.g. R. Elvik, 2007; Moons & Brijs, 2007; Sørensen & Elvik, 2007; Van Hout, Ariën, & Daniels, 2015). Notwithstanding, the implementation of DID at a larger scale (for instance at several of the rural-to-urban transitions) might have a positive influence on the safety culture as drivers are reminded of their driving speed every time they pass the DID. However, the implementation of automated section speed enforcement or intelligent speed adaption (ISA) might also have a positive effect on road safety (e.g. De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; F. Lai, Carsten, & Tate, 2012) and avoids the kangaroo effect after passing a DID. By means of an implementation at a larger scale, the road safety agency spreads the message that a correct driving speed is the societal norm and improves the 'shared responsibility' culture.

Once the specific road stretch is selected where a traffic intervention is required, the road safety agency and road designers should look at the **meso level**.

Concerning the transition from a rural to an urban area, the length of the problematic road stretch should be determined by means of network screening (e.g. Sørensen & Elvik, 2007; Van Hout et al., 2015). In case an inappropriate or excessive driving speed is measured at the entrance of the urban area, gate constructions proved to have the potential to improve road safety. However, when the problematic driving behavior is not limited to the direct vicinity of the entrance, additional traffic calming measures further along the road should be considered. Additional TCMs along the through route might help to further extend the speed reduction effect triggered by the gate. This is especially worthwhile to consider in thoroughfares with a residential function because vulnerable road users benefit even more from these speed reductions (R. Elvik, 2009, p. 50). Several studies established that the combination of gate constructions nearby the entrance of the urban area with additional traffic calming measures further along the through route are most effective (Harkey & Zegeer, 2004; Taylor and Wheeler, 2000; Village Speed Control Working Group, 1994; European Transport Safety Council, 1995). A combination with a DID might for instance increase the effectiveness the whole TCM scheme.

Furthermore, once a potential dangerous tangent-to-curve location is selected the specific TCM should be determined. The results showed that TRS were most effective on the tangent and the resulting lower driving speed gave the participants more time to form the right expectation about the upcoming curve. The HP on the other hand, reduced driving speed along the curve. The recommendation about which pavement marking is the most effective should therefore depend on the exact accident location nearby or in the curve. When accidents occur primarily near the curve entry, TRS is recommended because this measure reduces speed before entering the curve. The HP has the potential to reduce accidents at the curve end because it keeps driving speed at a lower level along the curve. In addition, TRS might have the highest benefits on curves with long tangents (such as the curves in this experiment) as TRS have the potential to reduce the high driving speeds which are often related to long tangents compared to shorter tangents. Furthermore, this experiment showed a more stable deceleration maneuver towards the curve when TRS were implemented on the tangent. In order to avoid that drivers accelerate again between the TRS and the curve it is important that there is a visual link between the TRS and the curve, which was the case in this configuration where the tangent was equipped with TRS between 166 and 50 m before the curve entry. The visual link between a TCM and the potentially dangerous situation or location is in general important in order to improve a feeling of credible speed management (SWOV, 2012) and to avoid compensating behavior (i.e., accelerating immediately after the TCM) or reducing effectiveness in time (Theeuwes et al., 2012).

Finally, once the specific location within the network and the road segment is selected, the design at the **micro level** should be considered. With regard to the installation of a gate we advise road designers to take different aspects into account to make this measure effective. For instance, in order to avoid frontal collisions, gate constructions should always be clearly visible and marked if necessary. Also, it should be avoided that drivers are required to execute (too) difficult steering wheel movements when they come along gates. Despite the favorable implications of TRS and HP in terms of road safety, Dewar and Olson (2007) warn for the potential negative side effects of both pavement markings such as noise, rapid wear, disruption of drainage and reduced tire-road surface friction. As an example, the Flemish Government (Agentschap Wegen en Verkeer, n.d., 2014) advises to interrupt the transversal rumble strip in the middle (50 cm) to improve the safety of motorcyclists. Furthermore, the experiment showed that the pavement marking produce no significant effects on lateral control parameters. Even though this is not the primary function of TRS or HPs, this finding should warrant policy makers not to consider these two road markings as a countermeasure in curves where accidents are mainly due inappropriate lateral control. Finally, we advise road designers to take the concept of *forgiving roads* into account where the road environment ensures that the consequences of an error are reduced to a minimum. According to the literature (La Torre, 2012; Nitsche et al., 2010; SWOV, 2010; Vlaamse Overheid, 2014), obstacle-free zones and collision-friendly obstacle protections are important design examples.

In summary, as the speed reduction effect of the TCM investigated is limited in distance, a good selection of the specific location to implement the TCM along the network and along the specific road segment is required in order to avoid excessive usage. Accident analysis, conflict observation techniques or speed measurements can support this selection. Finally, a safe and forgiving design of the TCM as such requires also sufficient attention.

5.3 APPLICATION OF DRIVING SIMULATOR RESEARCH IN GEOMETRIC ROAD DESIGN

Driving simulator research is considered as a suitable research tool in human-centered road design (see paragraph 2.1). Some important experiences which we were faced during the different driving simulator experiments are described below. Furthermore, the role of the driving simulator in the development process of human-centered road design is elaborated.

5.3.1 Important experiences during driving simulator experiments

First, validity and participant dropout are elaborated whereupon some advantages and disadvantages of longitudinal driving simulator experiments and the STISIM software are discussed. Finally, the need for a critical researcher attitude and a multidisciplinary supporting team is discussed.

Besides the various advantages of driving simulator research (e.g., pro-active, safe, cost efficient and easy data collection, advanced level of control over a wide range of factors etc.), the issue of **validity** is often raised when discussing the results of research employing driving simulations. Within the context of driving simulators, there are two types of validity: physical and behavioral validity (Blaauw, 1982; Blana, 1996). Physical validity refers to the extent to which the substantive elements of the simulator vehicle are matching the car on the road (including the layout of the simulator, visual displays and dynamics). Behavioral validity refers to the degree of similarity between the behavior generated in the driving simulator and driving in real life and is divided into two types of validity, namely absolute and relative validity (Mullen, Weaver, Riendeau, Morrison, & Bédard, 2010). Absolute validity is obtained when the simulated and the actual environment produce the same numerical values (i.e., no significant differences between the observations). When the simulated and the actual environment generate values which are not identical, but of which both the magnitude and the direction are similar, relative validity is obtained. In general, relative validity is more often achieved in driving simulator studies compared to absolute validity. However, research has shown that only relative validity is necessary for a driving simulator to be a useful research tool (absolute validity is not essential) (Bella, 2008; Godley et al., 2002; Törnros, 1998).

Although moving base simulators provide a more correct rendering of real driving behavior and a greater degree of realism (Bella, 2009), there are strong indications that geometric design issues are examinable in fixed-base driving simulators in a perfectly adequate way (e.g., Bella, 2007, 2008; Calvi et al., 2012; Charlton, 2004; Federal Highway Administration, 2007). Unfortunately we were not able to perform validation studies of the experiments in this thesis. Notwithstanding, a validation study of the newest version of the medium fidelity fixed-base driving simulator of the Transportation Research Institute (including STISIM M400 version 3 (instead of version 2 which was used in this thesis) and a real vehicle mockup) was recently performed (Cornu et al., 2016). The descriptive plot shows at first sight that the relative validity of the driving simulator for speed research on a horizontal curve seems to be high. However, a bilateral Z-test and a factorial univariate ANOVA based on 7 measurement points did not reveal any robust outcomes concerning the relative or absolute validity of the driving simulator. In general, the speeds recorded in real life were significantly higher than the speeds observed in the driving simulator for all other points. The latter is supported by other validation studies (e.g. Godley et al., 2002; Klee et al., 1999). Furthermore, the authors describe that the use of an ANOVA analysis may not always be robust in driving simulator validation research, since the outcome of this analysis can vary based on the number of measurement points that are taken into account. Findings indicated that relative validity is established in the case that only 4 measurement points (instead of 7 points) are being included in the statistical analysis. Additionally, a short post-questionnaire about their experience of driving in the driving simulator indicated that most of the participants believe in driving simulators to be a useful research tool (1 = poor/fully disagree; 7 = excellent/fully agree):

- Driving behavior in general: 4.07
- Estimating driving speed in general while driving in driving simulator: 3.86
- Estimating driving speed in curves while driving in driving simulator: 3.83
- Physical validity of driving simulator mock-up and surroundings: 4.26
- Visual representation (i.e., on a 180° field of view seamless curved screen) of road environment: 5.00

In addition, the seamless curved screen with a 180° field of view used in this study satisfies the prescribed minimum of 120° field of view for the correct estimation of longitudinal speed (Kemeny & Panerai, 2003). Moreover, this seamless curved screen avoids misalignment of the multiple displays which decreases the chance of simulator sickness (Fisher et al., 2011). Notwithstanding, 9% of all participants in the five experiments suffered from driving simulator sickness and their sampled driving behavior was excluded from the data analysis. This percentage is rather comparable with ranges reported by Mullen et al (2010). Another important factor in the **dropout of participants** during the experiment are technical problems. Especially in a longitudinal experiment where the same drivers participate during five successive days, a technical failure of the system which cannot be resolved immediately resulted in a dropout of eight participants (Ariën, Brijs, Brijs, et al., 2014; Ariën, Brijs, Vanroelen, et al., 2014) (see paragraph 3.2 and 4.2).

As described in the thesis (Ariën, Brijs, Brijs, et al., 2014; Ariën, Brijs, Vanroelen, et al., 2014) (paragraph 3.2 and 4.2), when it comes to testing the impact of infrastructural and/or technological treatments on drivers' behavior under conditions of repeated exposure, the literature available is rather scarce. The two **longitudinal experiments** in this thesis showed that the effect of the different test conditions on driving speed was independent of the day of the week. Although the established speed reduction effects sustained over the experimental period of five successive days, Table 18 shows that the absolute speed reduction effect was often higher in the comparable cross-sectional experiment (Ariën et al., 2013a, 2016) (i.e., paragraph 3.1 and 4.1). Based on our results and those from Jamson and Lai (2011) we recommend to provide participants with the opportunity to familiarize with the treatments under investigation. Although we tried to anticipate to the potential influence of novelty effects of TCM on mean speed by this quite unique experimental setup (besides the studies of S. Jamson & Lai, 2011; Rossi et al., 2013a, 2013b) where participants were repeatedly exposed during 5 successive days, we were unable to pronounce upon the long term effect of these TCM as in a before-after field experiment. Future research can thus focus on longer term driving simulator research, naturalistic driving studies and a before-after field experiment. Finally, novelty effects in driving simulator research should receive more attention. Shinar (2007, p. 763) describes a novelty effect as the phenomenon where "*people's reactions are more extreme to new systems than to existing ones*". Evidently, such novelty effects do not only apply to the simulator systems themselves, but also to the specific treatments (for instance TCMs) being tested. To gain more insight into this effect, one could compare the results of the longitudinal experiments (Ariën, Brijs, Brijs, et al., 2014; Ariën, Brijs, Vanroelen, et al., 2014) (paragraph 3.2 and 4.2) with a driving simulator experiment in which each participant is exposed several times in a single simulator session to the TCM, thus comparable with the study of Jamson and Lai (2011).

The main advantage of the **STISIM M400 software** is the ease of creating scenarios using a scenario definition language which uses a standardized code line including parameters for longitudinal and lateral position, shape, size etc. Although the number of parameters which can be defined by the researcher is relatively extensive, the creation of rather complex geometric road designs requires a lot of creativity of the researcher to 'play' with the code and combine different parameters. As a result, the implementation of geo-specific database modelling (i.e., replicating a real-world driving environment in a simulated virtual world (Yan et al., 2008b)) is rather time consuming. Nowadays, other driving simulator software packages might be able to transform 3D design models of future road environments more easily into a driving simulator environment.

Furthermore, the realization of the different driving simulator experiments showed that a **critical attitude** towards all methodological decisions made during the whole process (i.e., from problem definition to scenario design over data collection to data analysis) is important but time consuming. Due to a limited number of publications describing some general standardized procedures in driving simulator research, the researcher is required to go through a variety of published driving simulator experiments in order to solve methodological issues. Some examples of, at first sight easy looking questions, are related to for instance the preferred sample size, the instructions the researcher gives to the participants, the length of the practice session, the location and length of data analysis zones and points or the calculation of mean speed. Concerning the latter, Ariën et al. (2015) (paragraph 2.4) described in detail the processing of driving simulator data before the statistical analysis by means of interpolation and an integral formula. As described in the methodology, all raw simulator data in this thesis was interpolated to a 1 m distance interval before starting the data analysis. At the time the first study (Ariën et al., 2013a) (paragraph 3.1) was performed, we did not have the in-depth knowledge about this data preparation step yet. Therefore, the interpolation technique was not used in this specific study.

Finally, the support of a **multidisciplinary team** of for instance researchers with critical attitudes, a vehicle engineer maintaining the simulator hardware, a visual expert creating 3D models and statisticians is required. Sharing their knowledge and experience from different fields offers opportunities to solve ad hoc questions and to come up with innovative and creative ideas.

5.3.2 The role of the driving simulator in the evaluation process of human-centered road design

Road agencies are looking for an optimal allocation of their resources in order to improve road safety and can use cost-benefit and cost-effectiveness analysis to prioritize road safety measures (European Road Safety Observatory, 2006; SWOV, 2011b). The effects on road safety of a specific infrastructural measure (e.g. gate construction, DID or pavement markings) are compared with the investment costs. These investment costs relate to cost for planning, development, installation, maintenance, etc. A clear insight in the effects on road safety of new road design features before they are widespread implemented is thus crucial.

In this paragraph we focus on a general evaluation process which can be used to investigate in a proactive way the effects of geometric road design on road safety. In order to examine the safety potential of various geometric road designs, a number of existing research tools or techniques can be used. The classification of evaluation methods which is used to determine the potential of advanced driver assistance systems (Eckstein & Zlocki, 2013) is adapted and tailored to geometric design research (see Figure 65). Furthermore there are some similarities with the general phases in clinical trials which form the basis of a drug development process (Commissioner, 2015; 'Learn About Clinical Studies - ClinicalTrials.gov', n.d.).

In the framework of the proactive examination of the safety potential of geometric road design, five different evaluation methods are distinguished. The differences between the evaluation methods relate to the representation of the three elements of the 'driver-vehicle-environment' control loop. In the first stages of the evaluation process, several of these 'driver-vehicle-environment' elements are virtually simulated (grey elements in Figure 65). Throughout the different stages of the evaluation process, more real elements (blue elements) are incorporated leading to a higher validity of the evaluation because it gives a better representation of the real complex road environment. The different evaluation methods are shortly described below.

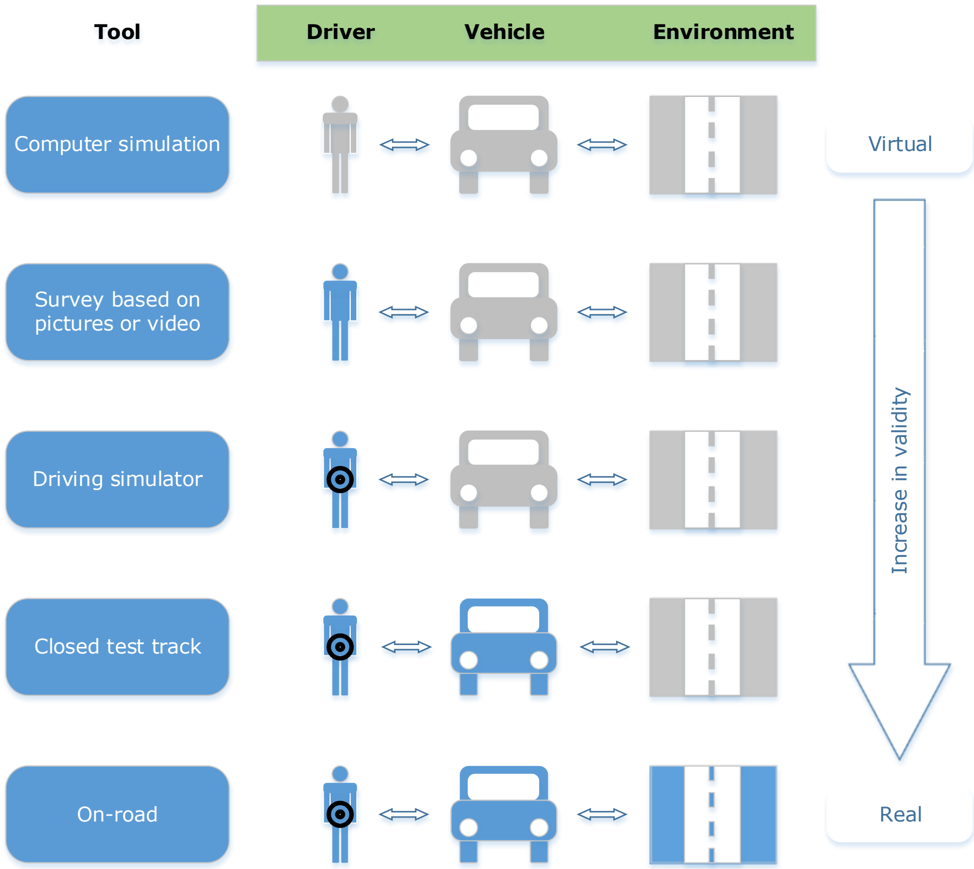


Figure 65 Classification of evaluation methods
(virtual elements in grey, real elements in blue)

Computer simulations: (Three-dimensional) software applications can simulate driving behavior of virtual drivers in a variety of virtual road environments and identify a range of road safety considerations including sight distance, traffic weaving and merge lengths (e.g. Vecovski, Mak, & Brisbane, 2009).

Survey based on pictures and video: In studies using laptop tests, participants are exposed to pictures and/or videos representing road environments containing TCMs, with rather general questions about the position of the TCM, understandability, readability, etc. The participants have to note their considerations and recommendations for the improvement of the measures under investigations (e.g., TCM). Laptop testing is a flexible and low-cost strategy allowing a wide range of TCM assessments, going from very practical questions about particular situations to more fundamental research questions relating to visibility, conspicuity, understandability and (stated) behavior. Important drawbacks are the limited dynamics and realism of the situations, which can lead to some biases introduced by the information provided by the researcher to the participant, and to incomplete input from the participant. Picture sorting tasks (e.g. Koszotolanyi-Ivan et al., 2016; Martens et al., 1998; Weller et al., 2008) are well known questionnaire studies in the field of road categorization research. The photo survey in Ariën, Cornu et al. (2014) (paragraph 3.3) shows an application of this evaluation method in this thesis.

Driving simulator: Two types of driving simulator studies can be distinguished. Either a virtually simulated road environment is created, or real-life video footage is being used. This thesis applied a driving simulator using virtual simulation and the main characteristics of this evaluation tool are described in paragraph 2.1.

Video footage based driving simulations offer a more realistic driving scene than traditional driving simulator studies where the road environment is virtually represented. Charlton (2006) used such a tool to study conspicuity, memorability, comprehension and priming of a number of different road hazard warning signs. Lai (2010, 2012) used a video footage based driving simulator to analyze the effects of different color schemes and message lines of VMS on driver performance, and to analyze drivers' comprehension of traffic information on graphical route information panels. These driving simulator studies are well-suited to study detection, readability and understanding of signage because the real-life road environment is represented in a more realistic setting than for instance in a laptop test. Yet, this technique generally does not provide many possibilities to directly study behavioral aspects since there are little possibilities to interact with the video. Indeed, participants are not really controlling their driving through the road scene, and thus not autonomously interacting with the road environment. Essentially, the vehicle mockup is mainly used as a context feature for the creation of a more realistic setting to show the video. Another disadvantage is that researchers only have limited control over the experiment because they cannot alter the recorded road environment. Yet, recent improvements in digital image processing allow to integrate virtual objects in a video-taped road environment. Notwithstanding, until so far, research (De Ceunynck et al., 2015; C.-J. Lai, 2010, 2012) using these more advanced techniques has only been focused on minor changes, such as the addition of a particular traffic sign or the replacement of an existing traffic sign by a different one.

Closed test track: An instrumented vehicle automatically records a number of driving parameters and can captures driver behavior on video while the driver passes a real-life test setting which is replicated on a closed test track. The collected data from an instrumented vehicle are also much richer and videos can be reviewed multiple times or by multiple researchers to ensure reliability and to increase the number of parameters that can be collected. A major challenge for experiments are the identification and analysis the interesting data from the huge data warehouses. An important disadvantage of the technique is that the cost of implementing a realistic test track can be very high. As this thesis focuses specifically on transitions and discontinuities, in which the total road environment plays an important role, the cost for replicating real environments on a closed test track might be very high. The interaction with other road users is also missing and makes the driving experience more artificial than on the public road.

On-road: On-road testing is highly realistic, but has some important drawbacks as well. Methodologically, the experimenter has only limited control. From an ethical perspective, the safety of study participants and other road users might be compromised, especially when being exposed to complex test situations. The data can be collected in three ways, i.e., on-site observation, in-vehicle observation with trained observers on board, and by means of an instrumented vehicle.

- On-site observations about the impact of TCMs collect observable generic characteristics of the vehicles passing a certain location and at specific moments in time (e.g. before implementation and weeks and months after the implementation). For example, Hallmark et al. (2007, 2008) examine the effects of different TCMs using pneumatic road tubes to collect speed and volume data before and at several points in time after the installation. Important advantages of on-site observations are the non-intrusive nature of the data collection (road users are generally unaware of being monitored) and the large sample size (i.e., all vehicles passing the study location within a certain time period).
- In studies that apply in-vehicle observations, participants drive a normal car while accompanied by one or more trained observers. The participant’s driving behavior is monitored by the observer(s) using a number of observable qualitative or quantitative indicators. An advantage is that more detailed driver behavior data can be collected than in on-site observations. An important drawback is that the presence of the observer(s) can lead to some test biases, for instance showing more socially desirable behavior.
- The instrumented vehicle automatically records a number of driving parameters and can captures driver behavior on video. This allows a less intrusive data collection because the researcher is not physically present in the vehicle, which can reduce some test biases (Dingus et al., 2006). The collected data from an instrumented vehicle are also much richer and

videos can be reviewed multiple times or by multiple researchers to ensure reliability and to increase the number of parameters that can be collected. Recently, small data loggers and smart phone technology makes the data collection on a larger scale very easy (e.g. Moreno & García, 2013). A major challenge for experiments are the identification and analysis the interesting data from the huge data warehouses. Limited control over the experiment can be an important drawback.

Finally, the validity of the evaluation tool can increase by the incorporation of **repeated exposure over a longer time period**. As infrastructural measures are installed for a longer time period (e.g. several years), the effects in time have to be considered as the result of a repeated exposure to the same measure in time. In field experiments speed measures are collected before the implementation and several weeks and months after the implementation of the TCM (e.g. Hallmark et al., 2007, 2008; Ullman & Rose, 2005). Driving simulator research in this context is rather scarce. In the studies of Jamson and Lai (2011) and Rossi et al. (2013a, 2013b) subjects participated during one single simulator session during which each participants passed respectively four and ten times the same infrastructural measurements. The experiments in this thesis (paragraph 3.2 and 4.2) are, to the best of our knowledge, unique because participants are exposed during five consecutive days to the same TCM.

The proposed evaluation process for a proactive evaluation of geometric road design should be further elaborated in future research. Especially the cost of the different evaluation tools and the benefits of the improved road safety (e.g. De Brabander & Vereeck, 2007) should be taken into account.

5.4 Traffic calming measures as part of a Self-Explaining Road network: Future research and challenges

Based on the results of the five driving simulator studies some ideas for future research on TCMs are formulated. In addition, future challenges with respect to TCM as part of a SER network are discussed.

5.4.1 Ideas for future research on traffic calming measures

Besides the different TCMs examined in this thesis, a variety of other different geometric design configurations exist. Future research could focus on such different configurations, try to determine the optimal location of the TCM with respect to the transition or discontinuity (e.g., what is the optimal distance between the TRS and the curve entry?), the optimal distance between the markings in the TRS or HP configuration or to investigate the influence of complementary TCMs along the thoroughfare or curve.

To gain more insight into novelty effects in driving simulator research, it might be interesting to compare the results of the longitudinal experiments in which each participant is exposed during five successive days with a driving simulator experiment in which each participant will be exposed several times in a single simulator session to the TCM, thus comparable with the study of Jamson and Lai (2011) and Rossi (2013a, 2013b). Furthermore, the longitudinal experiments were unable to report on the long term effect of these TCM as in a before-after field experiment. Future research can thus focus on longer term naturalistic driving studies and before-after field experiments and give more insight into the presence or absence of adverse side effects of the TCM such as behavioral compensations (e.g., kangaroo effect where drivers accelerate after the TCM) (Theeuwes et al., 2012) or noise, rapid wear, disruption of drainage and reduced tire-road surface friction in the context of pavement markings (Dewar & Olson, 2007).

Finally, the driving simulator is recognized as an important tool in the proactive evaluation of road geometry and infrastructural-related aspects (including positioning and design of traffic signs). Driving simulators have shown to be a useful tool in this respect and provide insight into road safety and operation (Bella, 2009; De Ceunynck et al., 2015; Keith et al., 2005; Transportation Research Board, 2007). A shift towards a more proactive evaluation is a core element of the Safe System Approach which aims to prevent accidents by means of the application of a human-centered road design. Such an approach differs from traditional reactive approaches that aim to solve problems after they occur in the field, such as black spot treatments (Wegman et al., 2008). The importance of a shift towards more proactive road safety planning is acknowledged by several important policy documents (e.g., AASHTO, 2010; European Parliament & Council of the European Union, 2008; RiPCORD-iSEREST, n.d.). Also safety researchers and policy makers in other fields such as aviation (e.g. Kontogiannis & Malakis, 2009), health care (e.g. Kessels-Habraken, Van der Schaaf, De Jonge, & Rutte, 2010), and the petrochemical industry (e.g. C. M. Burns, 2006) are highly aware of the importance of proactively preventing crashes from happening.

5.4.2 Future challenges of traffic calming measures as part of a Self-Explaining Road network

The traffic calming measures under investigation in this thesis are low-cost and relatively easy to put in practice. Therefore, these TCMs can serve as short-term measures in a road network which is not yet re-categorized, re-marked or redesigned taking the self-explaining road (SER) characteristics into account. As shown in this thesis, TCMs near transitions and discontinuities have the potential to reduce driving speed and serve as a mitigating measure. In addition, TCMs have a signaling function and have the potential to increase the attention level.

Because this long-term and expensive transformation process to a complete SER network has to be implemented step by step, not all road segments will have a SER environment yet. Furthermore, the build environment is an important aspect with respect to credible speed limits (Goldenbeld & van Schagen, 2007; Goldenbeld et al., 2006) and it will take decennia to change this build environment. Once the SER-characteristics are implemented on the whole road network, Brouwer and colleagues (2008) wonder whether clearly recognizable and distinguishable road segments are sufficient to elicit safe driving behavior. Therefore the authors define three advantages of a clear indication of transitions:

- Redundancy reduces the change of not observing the transitions.
- An explicit indication of the transitions or discontinuities (for instance by a TCM) can improve the recognizability of the new road category or the road discontinuity at locations where it is important that the transition or discontinuity is observed quite in advance.
- An explicit indication of the transitions or discontinuities can support the road user to link the road design of the transition or discontinuity with the following road category or discontinuity.

Drivers who are characterized by their loyalty with respect to road safety will be influenced more easily by the SER environment. The TCMs near transitions and discontinuities will lose their mitigating character for this type of drivers. However, the TCMs can still serve as a signaling function. Nevertheless, the mitigating function of the TCMs will remain for drivers who are less loyal with respect to road safety and keeping a safe driving speed. In addition, speed enforcement should complement the credible speed limits in order to enforce a safe driving speed.

The implementation of intelligent speed adaption (ISA) and self-driving vehicles (in which the driver should be able to take over the vehicle control at each moment) might raise the question whether TCMs are still relevant in order to improve road safety. TCM and the implementation of credible speed limits have the potential to support the driver in their attention allocation. Besides the various in-vehicle features which should warn drivers in dangerous situations, TCMs have a signaling function and can improve the level and focus of attention of the driver during their approach to the changing road environment. Further research about the dimensions and specific location of TCMs is thus advised (see paragraph 5.4.1).

Furthermore, a consistent implementation of the road categorization and its design elements (including the TCM at transitions and discontinuities) across the country (or the continent) will improve the recognizability of the road categorizations and will avoid confusion in the road user. However, as described in paragraph 5.2, a good selection of potentially dangerous locations to implement TCMs is essential in order to avoid excessive usage and reduce the positive road safety effects. In addition, a uniform implementation of the road categorization is a challenge as decentralized governments are often in charge to design and implement the uniform road design. Nowadays transitions and discontinuities are also often observed at local authority boundaries (Aarts et al., 2005; Brouwer et al., 2008; Charman et al., 2010). The 'shared responsibility' is here also an important issue.

Finally, although this thesis focusses specifically on road design, an holistic approach of the road transport system is required to improve road safety. Besides road design, countermeasures with respect to vehicles, road users, training and education, enforcements and a punctual road safety evaluation etc. are required. The combination of these elements is more effective than focusing on one single aspect (Matena et al., 2008; Salmon & Lenné, 2015).

5.4.3 Integration of research results in design standards

Road agencies and road designers use a wide variety of design manuals, handbooks and circulars to base their decision and design process on. National authorities often develop their own standards which might be based on international literature, own insights or purely recorded once in history (for instance several decades ago when the highway code was recorded). An important issue which has to be addressed is whether one may assume that safety is already appropriately incorporated in policies, manuals etc. (Hauer, 2016). In addition the following questions should be considered:

- How is new or additional information included in the manuals?
- How is existing information removed from the manuals?

As the guidelines and recommendations have an important influence on the selection and design of roads, these guidelines also have a direct or indirect influence on road safety, traffic flow, costs and environmental impacts. Therefore, the addressed questions are mainly important from a sustainable societal point of view and fit with the 'shared responsibility' concept of the Safe System Approach. This issue is also addressed by Wegman and Aarts (2006, p. 60): "*Many choices made in the handbooks are not yet based on scientific research. How much safety is lost if a designer deviates from a recommended 'optimum value' is too often not known*" and Salmon and Lenné (2015, p. 248): "*The challenge for the road safety community (researchers, practitioners, stakeholders) now is not only to further investigate systems thinking applications in road safety research, but also to translate research of this kind into practice*".

In an optimal situation, all guidelines should be linked with road safety resulting in the incorporation of the road safety aspects from the start of the design process. Unfortunately, some of the existing manuals and handbooks (e.g., Federal Highway Administration, 2012; Texas Department of Transportation, 2010; Transportation Research Board, 2000; Washington State Department of transportation, 2010) elaborate on road safety only in the introductory chapters and the specific design standards have only a limited link with road safety. Nevertheless, there are some good examples too in which the link with road safety research is clearly present (e.g., Campbell et al., 2008; CROW, 2004; R. Elvik et al., 2009). Schermers and colleagues (2013) reviewed three Dutch guideline documents (i.e., ASVV (urban traffic facilities), the Handbook for Road Design (rural roads) and NOA (motorways)) and established that a traffic safety element was only mentioned in just over 30% of the design elements.

With respect to the development of guidelines, Schermers et al. (2013) made a separation between countries which use working groups under guidance of private organizations on the one hand (e.g. Netherlands, Germany, USA) and countries where the government develops the guidelines internally (e.g. UK, Ireland) on the other hand. Concerning the specific situation in Flanders, there is no systematic approach to include results of local or international research in the guidelines and recommendations. In comparison with the Dutch situation (Wegman & Aarts, 2006), where the organization CROW is constantly looking for new results in order to bring their renewed publications to the market, the Flemish government creates the guidelines by themselves and provides them for free. As a result, there is probably also a weaker stimulus to actively look for new research results. In case the government recommends to carry out a specific research, it is more likely that these results will be incorporated in the guidelines (Bax, 2011). A specific example are the additions in the Flemish Guidelines for Safe Roads and Intersections (Vademecum Veilige Wegen en Kruispunten, (Agentschap Wegen en Verkeer, 2009)) which were based on the research of Daniels et al. (Daniels, Brijs, Nuyts, & Wets, 2010, 2011; Daniels, Nuyts, & Wets, 2008). However, there is no systematic approach to incorporate research results of studies which were not directly initiated by the government. Concerning the research in this thesis, only the geometric characteristics of TRS are included in the Flemish guidelines (Agentschap Wegen en Verkeer, n.d., pp. 2–35, 2014, pp. 79, 80), whereas no link is made to road safety effects. Furthermore, the Flemish Mobiliteitsbrief (Mobiel Vlaanderen, 2010) elaborates on the practical implementation of gate constructions at 70-to-50 kph transitions by illustration some practical cases. However, there is no link with specific guideline documents.

In a first step the government can look, together with the researchers and the road designer, for opportunities to transmit scientific results from the researchers to the road agency. More specifically, the translation from the results described in international scientific papers to a brief and synoptic overview can help the government to get a first insight in the results. Inspiration for this brief overview can be found in Campbell et al (2008), CROW (2004) and Elvik et al (2009). In a second phase the government can decide whether it is desirable to include the research results and their practical recommendations in the guidelines. Furthermore, additional research in other domains can complete the basic information about the guideline with respect to traffic flow, costs and environmental impact (e.g. Ahn & Rakha, 2009; R. Elvik et al., 2009; Montella, Galante, Mauriello, & Pariota, 2015b).

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Ph.D. student Traffic Safety
Promotor: Prof. dr. Tom Brijs

10/2013 – present
Hasselt University – Transportation Research Institute (IMOB)
Coordinator education of the bachelor and master of Mobiliteitswetenschappen and Transportation Sciences

EDUCATION

2008 – 2010
Master of Transportation Sciences – Traffic safety
Hasselt University
Degree: Summa cum laude
Master thesis: Driving simulator study on the effectiveness of different thoroughfare configurations
Promotor: Prof. dr. Tom Brijs
AXA-award: € 500

2005 – 2008
Bachelor of Transportation Sciences
Hasselt University
Degree: Magna cum laude
Bachelor thesis: Freight transport between the Economic Network Albertkanaal and the Kempen Axis (Vrachtverkeer tussen het Economisch Netwerk Albertkanaal en de Kempische As)
Promotor: Prof. dr. Tom Brijs

1999 - 2005
Science and mathematics
Rozenberg S.O., Mol

JOURNAL PUBLICATIONS - PUBLISHED

- **ARIËN, Caroline**; BRIJS, Kris; VANROELEN, Giovanni; CEULEMANS, Wesley; JONGEN, Ellen M.M.; DANIELS, Stijn; BRIJS, Tom; WETS, Geert (2016) The effect of pavement markings on driving behavior in curves: a simulator study. In *Ergonomics*, doi: 10.1080/00140139.2016.1200749. [web of science: 5 year impact factor 1.804]
- DE CEUNYNCK, Tim; **ARIËN, Caroline**; BRIJS, Kris; BRIJS, Tom; VAN VLIERDEN, Karin; Kuppens, Johan; Van der Linden, Max & WETS, Geert (2015). Proactive Evaluation of Traffic Signs Using a Traffic Sign Simulator. *European Journal of Transport and Infrastructure Research, 15* (2), p. 184-204. [web of science: 5 year impact factor 1.144]
- **ARIËN Caroline**; BRIJS Kris; BRIJS Tom; CEULEMANS Wesley; VANROELEN Giovanni; JONGEN Ellen M. M.; DANIELS Stijn; WETS Geert (2014). Does the effect of traffic calming measures endure over time? – A simulator study on the influence of gates. *Transportation Research Part F: Traffic Psychology and Behaviour, 22*, 63–75. doi:10.1016/j.trf.2013.10.010. [web of science: 5 year impact factor 2.349]
- BABAEE, Seddigheh; SHEN, Yongjun; HERMANS, Elke; WETS, Geert; BRIJS, Tom; **ARIËN, Caroline** (2014). Combining driving performance information in an index score: a simulated curve-taking experiment. *Transportation Research Record, 3952* (2434), p. 44-51.
- **ARIËN Caroline**; JONGEN Ellen M.M.; BRIJS Kris; BRIJS Tom; DANIELS Stijn; WETS Geert (2013). A Simulator Study on the Impact of Traffic Calming Measures in Urban Areas on Driving Behavior and Workload. *Accident Analysis & Prevention, 61,* 43–53. doi:10.1016/j.aap.2012.12.044. [web of science: 5 year impact factor 3.096].
- **ARIËN Caroline**; HERMANS Elke (2012). Verkeersveiligheid in 2015: doorrekening van een aantal maatregelen uit het Verkeersveiligheidsplan Vlaanderen. *Verkeersspecialist*, nr. 189.

JOURNAL PUBLICATIONS – IN REVIEW

- **ARIËN, Caroline**; BRIJS, Kris; VANROELEN, Giovanni; CEULEMANS, Wesley; JONGEN, Ellen M.M.; DANIELS, Stijn; BRIJS, Tom; WETS, Geert (n.d.) A driving simulator study on the effect oftransversal rumble strips located nearby dangerous curves under repeated exposure. Submitted for first review in *European Journal of Transport and Infrastructure Research* [web of science: 5 year impact factor 1.144].
- **ARIËN, Caroline**; VANROELEN, Giovanni; BRIJS, Kris; JONGEN, Ellen M.M.; CORNU, Joris; ROSS, Veerle; MOLLU, Kristof; DANIELS, Stijn; BRIJS, Tom; WETS, Geert (n.d.) Processing driving simulator data before

statistical analysis by means of interpolation and a simple integral formula. Submitted for first review in *Transportation Research part B* [web of science: 5 year impact factor 4.116].

- **ARIËN, Caroline**; CORNU, Joris; BRIJS, Kris; BRIJS, Tom; VANROELEN, Giovanni; JONGEN, Ellen M.M.; DANIELS, Stijn; WETS, Geert (n.d.) Measuring the impact of digital information displays on speed: A driving simulator study. Submitted for first review in *Accident Analysis and Prevention*. [web of science: 5 year impact factor 2.699].

CONFERENCE PUBLICATIONS

- CORNU, Joris; **ARIËN, Caroline**; GARDENIERS, Beau; BRIJS, Kris; DANIELS, Stijn; BRIJS, Tom; WETS, Geert (2016). *Driving simulator validation for speed research on a horizontal curve.* In: Proceedings of Transportation Research Board 95th Annual Meeting (abstract proceedings). Washington D.C., (U.S.), January 10-14, 2016.
- **ARIËN Caroline**; BRIJS Kris; CEULEMANS Wesley; VANROELEN Giovanni; JONGEN Ellen M.M.; DANIELS Stijn; BRIJS Tom; WETS Geert (2014) *A driving simulator study on the effect of transversal rumble strips located nearby dangerous curves under repeated exposure.* In: Proceeding of the 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014, Kraków (Poland), July 19-23, 2014.
- BABAEE Seddigheh; SHEN Yongjun; HERMANS Elke; WETS Geert; BRIJS Tom; **ARIËN Caroline** (2014) *Assessing individual driver’s relative performance at curve: applying Data Envelopment Analysis on simulator data.* In: Proceedings of Transport Research Arena 2014 (TRA2014) Transport Solutions: from Research to Deployment - Innovate Mobility, Mobilise Innovation. Paris La Défense (France), April 14-17, 2014.
- DE CEUNYNCK Tim; **ARIËN Caroline**; BRIJS Kris; BRIJS Tom; VAN VLIERDEN Karin; KUPPENS Johan; VAN DER LINDEN Max; WETS Geert (2014) *Proactive evaluation of traffic signs using a traffic sign simulator.* In: Proceedings of Transportation Research Board 93rd Annual Meeting. Washington D.C., (U.S.), January 12-16, 2014.
- BABAEE Seddigheh; SHEN Yongjun; HERMANS Elke; WETS Geert; BRIJS Tom; **ARIËN Caroline** (2014) *Combining driving performance information in an index score: A simulated curve-taking experiment.* In: Proceedings of Transportation Research Board 93rd Annual Meeting. Washington D.C., (U.S.), January 12-16, 2014.
- **ARIËN Caroline**; BRIJS Kris; BRIJS Tom; CEULEMANS Wesley; VANROELEN Giovanni; JONGEN Ellen M. M.; DANIELS Stijn; WETS Geert (2013). *Does the effect of traffic calming measures endure over time? – A simulator study on the influence of gates.* In: Proceedings of 4th International Conference on Road Safety and Simulation (RSS 2013), Rome (Italy), October 23-25, 2013.

- **ARIËN Caroline**; CORNU Joris; BRIJS Kris; BRIJS Tom; VANROELEN Giovanni; JONGEN Ellen M.M.; DANIELS Stijn; WETS Geert (2013). *Measuring the impact of digital information displays on speed: A driving simulator study.* In: Proceedings of Transportation Research Board 92nd Annual Meeting. Washington D.C., (U.S.), January 13-17, 2013.
- **ARIËN, Caroline**; DE CEUNYNCK, Tim; BRIJS, Kris; BRIJS, Tom; VAN VLIERDEN, Karin; Kuppens, J.; Van Der Linden, M & WETS, Geert (2013). *Ex-ante evaluatie van wegsignalisatie met een rijsimulator.* In: Jaarboek Verkeersveiligheid 2013, p. 90-93. Vlaams Congres Verkeersveiligheid, Antwerp (Belgium), May, 16, 2013.
- **ARIËN, Caroline**; BRIJS, Kris; CEULEMANS, Wesley; VANROELEN, Giovanni; JONGEN, Ellen; DANIELS, Stijn; BRIJS, Tom & WETS, Geert (2013). *Een rijsimulatorstudie over het langdurige effect van snelheidsverlagende maatregelen.* In: Proceedings van het Belgisch Wegencongres, Luik (Belgium), September, 11-13, 2013.
- DE CEUNYNCK Tim; **ARIËN Caroline**; BRIJS Kris; BRIJS Tom; VAN VLIERDEN Karin; KUPPENS Johan; VAN DER LINDEN Max; WETS Geert (2012). *Ex-ante evaluation of traffic signs using a Traffic Sign Simulator.* In: online Proceedings of 25th International Co-operation on Theories and Concepts in Traffic Safety (ICTCT 2012). Diepenbeek (Belgium), November, 8-9, 2012.
- **ARIËN Caroline**; BRIJS Kris; CEULEMANS Wesley; VANROELEN Giovanni; BRIJS Tom; WETS Geert (2012). *Driving behavior at transitions from motorways to secondary roads: A driving simulator study.* In: Proceedings of 5th International Conference of Traffic and Transport Psychology (ICTTP 2012). Groningen (The Netherlands), August, 29-31, 2012.
- **ARIËN Caroline**; HERMANS Elke (2012). *Verkeersveiligheid in 2015: doorrekening van een aantal maatregelen uit het verkeersveiligheidsplan Vlaanderen.* In: online Proceedings of Vlaams Congres Verkeersveiligheid. Gent (Belgium), May 22, 2012.
- **ARIËN Caroline**; BRIJS Kris; CEULEMANS Wesley; JONGEN Ellen M.M.; DANIELS Stijn; BRIJS Tom; WETS Geert (2012). *The effect of pavement markings on driving behavior in curves: A driving simulator study.* In: Proceedings of Transportation Research Board 91st Annual Meeting. Washington D.C., (U.S.), January 22-26, 2012.
- **ARIËN Caroline**; HERMANS Elke; WETS Geert & BRIJS TOM (2011). *Assessing the impact of road safety policy measures at the regional level: modelling approach and application.* In: Proceedings of the 24th ICTCT Workshop (abstract proceedings). Warsaw (Poland), October 27-28, 2011.
- **ARIËN Caroline**; JONGEN Ellen M.M.; BRIJS Kris; BRIJS Tom & WETS Geert (2011). *A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload.* In: Proceedings of Transportation Research Board 3rd International

Conference on Road Safety and Simulation (RSS 2011). Indiana (U.S.), September 14-16, 2011.

REPORTS

- VAN HOUT, Kurt; **ARIËN, Caroline**; DANIELS, Stijn (2015). *Network Safety Management. Een ranking van gevaarlijke segmenten op de autosnelwegen van het TEN-T netwerk in Vlaanderen – eindrapport*. Steunpuntrapport RA-2015-003. Diepenbeek (Belgium): Steunpunt Verkeersveiligheid.
- **ARIËN Caroline**; HERMANS Elke; REUMERS Sofie; DANIELS Stijn; WETS Geert; BRIJS Tom (2012). *Assessing the impact of road safety policy measures in Flanders: modelling approach and application.* Steunpuntrapport RA-MOW-2011-025. Diepenbeek (Belgium): Steunpunt Mobiliteit en Openbare Werken, spoor Verkeersveiligheid.
- BRIJS Kris; **ARIËN Caroline**; DE CEUNYNCK Tim; BRIJS Tom; VAN VLIERDEN Karin; KUPPENS Johan, VAN DER LINDEN Max; WETS, Geert (2011). *Signalisatiesimulator Signalisatieplan bedrijventerrein Genk.* Uitgevoerd in opdracht van Agentschap Wegen en Verkeer (AWV) Limburg.
- BRIJS Kris; **ARIËN Caroline**; BRIJS Tom; VAN VLIERDEN Karin; KUPPENS Johan; VAN DER LINDEN Max; WETS, Geert (2011). *Signalisatiesimulatie Werken Aan R7 Viaduct te Vilvoorde.* Uitgevoerd in opdracht van Agentschap Wegen en Verkeer (AWV) Vlaams Brabant.

COMPETENCES

Technical skills

- Conceptual thinking: developing new research topics, solving acute problems
- Planning and organizing: developing and executing research, collecting data
- Analyzing data: analyzing specific data into useful information (for instance policy recommendations)
- Computer skills:
    - Advanced knowledge of Word, Excel, Powerpoint, Outlook, Visio and STISIM simulator definition language
    - Intermediate knowledge of Access, Visio, SPSS and MySQL
    - Basic knowledge of R, TransCAD and AutoCAD

Communication

- Writing skills: writing of reports and journal articles
- Presenting and teaching
- Meeting with team and experts, networking
- Evaluating: reviewing of reports, evaluation of theses

Language skills

- Presenting on (inter)national conferences in Dutch and English
- Teaching in Dutch and English
- Writing publications in Dutch and English

	Reading	Spoken	Writing
Dutch		Native language	
English	Advanced	Advanced	Advanced
French	Intermediate	Basic	Basic

Other skills

- Mentor work in the education program of Transportation Sciences at Hasselt University
- Supervision of master theses as co-promoter

MEMBERSHIPS

- Member of the research group Traffic Safety, Hasselt University – Transportation Research Institute
- Member of the education team at Hasselt University: Traffic sciences 1, Traffic sciences 2, Current topics of transportation sciences, Road safety evaluation: methods and applications, Internship and Master thesis