Table of Contents

List of Tables

List of Figures

List of Equations

Acknowledgements

This doctoral thesis is the outcome of a PhD research carried out at the Transportation Research Institute (IMOB) of Hasselt University. It took me four years to complete this research. After the completion of my PhD, I am deeply grateful to a lot of persons who helped me achieve one of the most important milestones in my life.

First of all, I would like to thank my promotor Prof. Tom Brijs and my co-promotor Prof. Ali Pirdavani MSc for guiding me throughout the past four years of my PhD. Their advice and help at crucial moments made it easier for me to complete this thesis. Due to their kindness, trust and consistent support, my PhD went smoothly without too many ups and downs. I would also like to thank my other doctoral committee members Prof. Geert Wets and Prof. Ansar-Ul-Haque Yasar. They provided me with an opportunity to work in a highly professional environment.

I would also like to offer my deepest and sincerest gratitude to Dr. Muhammad Adnan for sparing time, despite having a busy schedule and helping me at various important stages. I also wish to thank my colleagues at IMOB especially Dirk Roox and Marc Geraerts who helped me a lot in designing driving simulator scenarios for which I am very thankful. I am also grateful to the Higher Education Commission (HEC) Pakistan for their financial support during this PhD period. Without their financial support, completing this PhD would have been very difficult.

Last but not least, I would like to thank my family and friends who encouraged and supported me during this time period. I would like to dedicate this effort to my parents, especially to my father Nazar Hussain Nazar, and my brother Dr. Jawad Hussain who motivated me to continue my studies after completion of my Masters and provided with the moral support I required. I am sincerely thankful to the love of my life, my wife who supported me morally and emotionally during my stay in Belgium. Of course, it was really difficult for her to stay away for such a long duration but her patience and courage increased my motivation for completing my PhD. My friends, both here in Belgium and in Pakistan helped me a lot in overcoming many desperate, depressing and frustrating times, something

I will never forget and for which I am profoundly grateful. Especially my friends Usman Ashraf and Shah Rukh Sajid gave me a shoulder to cry on when I was feeling blue. I could not have done it without the support from all of my friends.

Hammad Hussain Awan

Summary

Road safety is a very important problem being faced by all the countries at different levels. Road casualties share a major part in social and economic losses (Section 1.1). Various strategies have been adopted by different countries to counter this problem. These strategies are based on previous research which highlighted the causes of road crashes (Section 1.2). One of these major causes is driving behaviour, which contributes more than 90 percent of crash occurrences. Hence, it is important that drivers' behaviour should be given due importance in the safety evaluation of road designs. Various strategies such as Vision zero and sustainable safety define various prospects at which the problem of road safety can be dealt with. Indeed, road designs should be able to accommodate all types of road users including cyclists, pedestrians etc. the focus of this thesis is however on car drivers. One of the factors which can considerably improve driving behaviour is by making road designs understandable to the drivers and in line with the drivers expectations. The design philosophy of self-explaining roads is centred around this theme (Section 1.2.3). This means that road designs provide clear perception of the type of behaviour required at certain sections of the road in order to be safe.

To evaluate the safety of a road design, a road safety audit procedure is followed (Section 1.2.5). For the evaluation of road designs in the planning phase, the common current practices do not involve common drivers directly as the standards provide auditors with checklists. These checklists are mainly centred around various geometric design aspects. The drivers' behaviour consideration in safety audits greatly rely upon the auditor's experience. One way to involve the drivers in both design and safety processes is by allowing them to experience the road design before it is built in the real world. In this way, design errors can be mitigated before they happen in real life and hence, can considerably save economic and social losses.

Driving simulators are excellent tools which provide a control virtual environment to drivers in which they can experience new road designs while driving through them in a safe environment. They allow us to collect data for various driving behaviour parameters for the designs that are yet to be constructed in the real

world. However, the methodology and the selection of the driving simulator type greatly depends upon the type of research question that needs to be addressed. Chapter 2 of this thesis provides detailed explanations about driving simulators in which different types of driving simulators, based on their level of fidelity, their advantages and disadvantages, designing of the experimental methodology, and appropriate selection of human driving behaviour parameters are discussed in detail.

This doctoral thesis aims to highlight the importance of the involvement of common drivers in the safety evaluation of new road designs by the use of driving simulators in a proactive way so that possible social and economic losses can be avoided. This will help further in increasing the quality of road safety. This aim leads towards defining the objectives of this thesis which are;

- To show that the driving simulators are useful tools in evaluation of alternative road designs prior to their construction;
- To demonstrate that the driving simulators are useful tools to study human driving behaviour in relation to the safety evaluation of road designs.

To achieve these objectives, three driving simulator studies were designed. The driving simulator studies in this thesis evaluated different road designs before their actual construction in the real world. These road designs were located at the discontinuities in the road network. These discontinuities were: separation between express and local lanes on freeways, merging of freeways, and a sharp horizontal curve on a two-way rural road. The evaluation of the road designs was done with respect to driving behaviour parameters. The driving simulator studies showed that indeed there were significant differences found in human driving behaviour parameters for different conditions. This verifies the usefulness of driving simulators in evaluation studies for various road designs.

In chapter 3, we analysed alternate ways of separating express and local lanes than hard separation. Four different separation types were compared with each other by evaluating drivers’ crossing behaviour and their temptations to cross the separation in relation to two control conditions. As it is important that even though a soft separation can provide an escape route to the traffic in express lanes in a traffic jam, the soft separation should be able to restrict drivers to make illegal lane changes between express and local lanes. Results show that the probability of high temptations to cross is least for tubular delineators and vegetation strip. Hence, the study concluded that tubular delineators and vegetation strips are more effective in restricting drivers to cross the lanes. This provides an empirical solution for the replacement of hard separations on freeways. The study contributes in achievement of the general objectives of the thesis as it showed significant results for the type of separation.

Chapter 4 of this doctoral thesis investigated the performance of two freeway merging designs with a decreasing number of lanes. The designs were created in a driving simulator environment according to Dutch road design guidelines. Traffic conditions (intensity to capacity ratio, percentage of heavy vehicles)were kept under the maximum allowable limits described in the standards. The effects of different heavy vehicles were investigated in relation to human driving behaviour parameters mean speed, acceleration, standard deviation of acceleration deceleration, and cumulative lane changes. The performance of the two designs (standard and taper), was then compared with each other. It was found that under the selected traffic conditions, standard design was safer than the taper design. The study provided empirical conclusions which can help designers in selection of road designs. The study contributes in the achievement of the general objectives of the thesis as it provides designers with arguments for the selection of a merging freeway road design with a decreasing number of lanes.

In the third and last case study of this thesis included in Chapter 5, two road markings were implemented before and during a sharp horizontal curve. The effects of these two markings (optical circles and herringbone pattern) on human driving behaviour were investigated. The human driving behaviour parameters that were selected for this study were mean speed and mean lateral position. Previous literature states that appropriate magnitude of these two parameters through curves can ensure safety through curves. Two horizontal curves were selected from the Belgian road network and recreated as realistically as possible in the driving simulator. The results show that optical circles significantly reduce the approach speed of the drivers before curves. Herringbone patterns significantly improved the lateral position of the drivers in the curve. The study concluded that locations where majority of crashes occur due to inappropriate speed, optical circles can be an economical option whereas curve locations where lateral position is the major cause of crashes, herringbone patterns can be used. This further supports us in achievement of our general objectives as both road markings are investigated before their implementation in the real world.

The final chapter (Chapter 6) of this thesis consists of general conclusions based on the three case studies carried out in this thesis. In general, the conclusion that can be drawn from the three case studies is that driving simulators are effective and efficient tools and should be used for the safety evaluation of road designs. Since the evaluation of road designs is done through the process of road safety audits, driving simulator studies should be an integral part of the process during pre-construction stages. Moreover, key findings and policy implications from the three case studies are also included. The limitations of the study such as the use of a fixed base driving simulator, the methodology design of the studies such as driving simulator program limitations for scenario creation, controlling vehicles in traffic stream, consideration of perspectives of car drivers, and experimentation such as recruitment of participants etc. are also explained in the last part of this chapter.

Samenvatting

Verkeersveiligheid is een zeer belangrijk probleem waarmee alle landen geconfronteerd worden op verschillende niveaus. Dodelijke ongevallen leiden tot grote sociale en economische verliezen (Deel 1.1). Verschillende landen hebben verschillende strategieën gebruikt om dit probleem tegen te gaan. Deze strategieën zijn gebaseerd op eerdere onderzoeken waarbij de nadruk lag op de oorzaken van verkeersongevallen (Deel 1.2). Een van de belangrijke oorzaken is het rijgedrag, dat meer dan 90 procent van de ongevalsoorzaken vertegenwoordigt. Daarom is het belangrijk dat het rijgedrag van bestuurders een belangrijke rol krijgt bij de veiligheidsevaluatie van wegontwerpen. Verschillende strategieën, zoals Vision Zero en Duurzaam Veilig, definiëren verschillende perspectieven waarbij het probleem van de verkeersveiligheid aangepakt kan worden. Het is waar dat wegen zodanig ontworpen moeten dat zij geschikt zijn voor alle soorten weggebruikers, zoals fietsers, voetgangers enz. Dit proefschrift concentreert zich op automobilisten. Een van de factoren die het rijgedrag aanzienlijk kunnen verbeteren is het begrijpelijk maken van wegontwerpen voor bestuurders, in overeenstemming met de verwachtingen van de bestuurders. Dit thema is de centrale ontwerpfilosofie van zelfverklarende wegen (Deel 1.2.3). Dit betekent dat het wegontwerp duidelijk aangeeft welk soort gedrag nodig is op een bepaald deel van de weg om veilig te zijn.

Om de veiligheid van een wegontwerp te evalueren, wordt de verkeersveiligheidsauditprocedure gevolgd (Deel 1.2.5). Voor de evaluatie van wegontwerpen in de planningsfase worden bestuurders momenteel echter niet direct betrokken aangezien audits normaal gezien gedaan worden aan de hand van controlelijsten. Deze controlelijsten zijn hoofdzakelijk gericht op verschillende geometrische ontwerpaspecten. Het beoordelen van het rijgedrag van bestuurders is bij veiligheidsaudits daarom sterk afhankelijk van de ervaring van de auditor. Een manier om bestuurders direct te betrekken bij zowel ontwerp- als veiligheidsprocessen is door hen in staat te stellen een wegontwerp te ervaren voordat deze daadwerkelijk aangelegd wordt. Zo kunnen ontwerpfouten aangepakt worden voordat een weg wordt aangelegd, waardoor er aanzienlijk bespaard kan worden op economische en sociale verliezen.

Rijsimulatoren zijn uitstekende hulpmiddelen die een gecontroleerde virtuele omgeving kunnen bieden waarin bestuurders nieuwe wegontwerpen kunnen ervaren tijdens het rijden in een veilige omgeving. Ze stellen ons in staat om gegevens te verzamelen voor verschillende rijgedragparameters voor ontwerpen die nog aangelegd moeten worden. Echter, de methodologie en de selectie van het rijsimulatortype is sterk afhankelijk van de onderzoeksvraag die behandeld moet worden. Hoofdstuk 2 van dit proefschrift bevat een gedetailleerde uitleg over rijsimulatoren waarin de verschillende soorten rijsimulatoren uitvoerig besproken worden op basis van hun realisme, hun voor- en nadelen, het ontwerpen van de experimentele methodologie, en de aangewezen selectie van menselijke rijgedragparameters.

Dit proefschrift wil het belang onderstrepen van het betrekken van bestuurders bij de veiligheidsevaluatie van nieuwe wegontwerpen door het proactieve gebruik van rijsimulatoren, zodat mogelijke sociale en economische verliezen vermeden kunnen worden. Dit zal de kwaliteit van de verkeersveiligheid verder verhogen. Dit doel leidt tot het bepalen van de doelstellingen van deze thesis, met name;

- Aantonen dat rijsimulatoren nuttig zijn bij de beoordeling van alternatieve wegontwerpen vooraleer deze aangelegd worden;

- Aantonen dat rijsimulatoren nuttig zijn om het rijgedrag van de mens te bestuderen met betrekking tot de veiligheidsevaluatie van wegontwerpen.

Om deze doelstellingen te behalen werden drie rijsimulatorstudies ontworpen. De rijsimulatorstudies in deze thesis evalueerden verschillende wegontwerpen alvorens ze daadwerkelijk aangelegd werden. Deze wegontwerpen waren gemaakt voor 1) transities/discontinuïteiten in het wegennet, zoals de scheiding tussen doorgaande rijstroken en lokale rijstroken op autosnelwegen, 2) het samenvoegen van snelwegen en 3) een scherpe bocht op een plattelandsweg met tweerichtingsverkeer. De wegontwerpen werden geëvalueerd aan de hand van rijgedragparameters. De rijsimulatorstudies toonden aan dat er inderdaad significante verschillen waren in de menselijke rijgedragparameters voor verschillende omstandigheden. Dit bevestigt het nut van rijsimulatoren in evaluatiestudies voor verschillende wegontwerpen.

Concreet analyseerden we in hoofdstuk 3 alternatieve manieren om een scheiding te maken tussen doorgaande rijstroken en lokale rijstroken. Vier verschillende scheidingstypes werden met elkaar vergeleken op basis van de evaluatie van het oversteekgedrag van bestuurders en de verleiding die zij ervaarden om de scheiding over te steken met betrekking tot twee controlevoorwaarden. Het is belangrijk dat, alhoewel een zachte scheiding een vluchtroute kan bieden aan het verkeer dat zich bevindt op doorgaande rijstroken wanneer het vast zit in een verkeersopstopping, dit type scheiding bestuurders moet verhinderen om onwettige rijstrookveranderingen te maken tussen doorgaande rijstroken en lokale rijstroken. De resultaten tonen aan dat de verleiding om over te steken het laagst is bij gebruik van scheidingspaaltjes en beplante scheidingsstroken. Daarom concludeerde de studie dat scheidingspaaltjes en beplante scheidingsstroken effectiever zijn bij het verhinderen van bestuurders om rijstroken over te steken. Dit biedt een empirische oplossing voor de vervanging van harde scheidingen op snelwegen. De studie draagt bij tot de verwezenlijking van de algemene doelstellingen van het proefschrift omdat het significante resultaten toont voor het type scheiding.

Hoofdstuk 4 van dit proefschrift onderzoekt het wegontwerp voor het samenvoegen van twee snelwegen met een afnemend aantal rijstroken. De ontwerpen werden gemaakt in een rijsimulatoromgeving volgens de Nederlandse wegontwerprichtlijnen. De verkeersomstandigheden (verhouding intensiteit/capaciteit, percentage van zware voertuigen) werden gehouden onder de maximaal toegestane limieten, zoals beschreven in de richtlijnen. De impact van verschillende zware voertuigen werd onderzocht met betrekking tot de menselijke rijgedragparameters gemiddelde snelheid, versnelling, standaardafwijking van versnelling/vertraging en het cumulatief aantal rijstrookwissels. De prestaties van het standaard ontwerp en het taperontwerp werden vervolgens vergeleken met elkaar. Onder de gekozen verkeersomstandigheden bleek het standaardontwerp veiliger te zijn dan het taperontwerp. De studie leverde empirische conclusies op die de ontwerpers kunnen helpen bij de selectie van een wegontwerp. De studie draagt bij tot de verwezenlijking van de algemene doelstellingen van het proefschrift aangezien het de ontwerper argumenten biedt voor de selectie van een wegontwerp wanneer snelwegen samengevoegd worden met een afnemend aantal rijstroken.

In de derde en laatste casestudy van dit proefschrift, dat beschreven wordt in Hoofdstuk 5, werden twee wegmarkeringen aangebracht vóór en in een scherpe bocht. De effecten van deze twee markeringen (optische cirkels en visgraatpatronen) op het menselijke rijgedrag werden onderzocht. De menselijke rijgedragparameters die geselecteerd werden voor deze studie waren de gemiddelde snelheid en de gemiddelde laterale positie. Eerder onderzoek wees uit dat de juiste waarde van deze twee parameters in bochten de veiligheid van bochten kan verbeteren. Er werden twee bochten gekozen uit het Belgische wegennet en deze werden zo realistisch mogelijk nagemaakt in de rijsimulator. De resultaten tonen aan dat optische cirkels de snelheid van het aankomend verkeer aanzienlijk verlagen bij het naderen van bochten. Visgraatpatronen leiden tot een aanzienlijke verbetering van de laterale positie van bestuurders in bochten. De studie toonde aan dat bij locaties waar onaangepaste snelheid de grootste oorzaak van ongevallen was, optische cirkels een voordelige optie kan zijn terwijl bij bochten waar de laterale positie de belangrijkste oorzaak is van ongevallen, visgraatpatronen gebruikt kunnen worden. Dit helpt ons verder op weg bij het bereiken van onze algemene doelstellingen aangezien beide wegmarkeringen onderzocht worden alvorens ze te implementeren.

Het laatste hoofdstuk (Hoofdstuk 6) van dit proefschrift bevat algemene conclusies op basis van de drie case studies die in dit proefschrift uitgevoerd werden. De algemene conclusie die getrokken kan worden uit de drie case studies is dat rijsimulatoren effectieve en efficiënte instrumenten zijn die gebruikt zouden moeten worden voor de veiligheidsevaluatie van wegontwerpen. Aangezien wegontwerpen geëvalueerd worden door middel van verkeersveiligheidsaudits, zouden rijsimulatorstudies een integraal onderdeel van het proces moeten uitmaken in het stadium voorafgaand aan de wegconstructie. De belangrijkste bevindingen en beleidsimplicaties van de drie case studies zijn bovendien ook opgenomen. De beperkingen van de studie, zoals het gebruik van rijsimulatoren met een vaste basis, het methodologisch ontwerp van de studies, zoals programmeerbeperkingen bij het creëren van scenario’s voor rijsimulatoren, het regelen van voertuigen in de verkeerstroom, het rekening houden met de perspectieven van automobilisten, en experimenten zoals het rekruteren van deelnemers enz., worden eveneens toegelicht in het laatste deel van dit hoofdstuk.

1 Introduction

1.1 Problem of road safety

All developed, developing and under-developed countries are facing road safety problem at different extents and need to urgently act to alleviate this concern. According to the World Health Organization, approximately 1.3 million deaths are recorded per year and the loss of almost 3% of gross domestic product (GDP) was contributed to traffic-related injuries and mortalities (WHO 2015). Moreover, road fatality is a major cause of death among the age group between 15-29 years. This is an alarming situation as the majority of the productive population of any country belongs to this age group. The WHO report (WHO 2015) also shows that the total number of deaths (1.25 million in 2013) has remained approximately constant despite the increase in motorization, population, and the predicted rise in deaths. This shows that interventions to improve global road safety have prevented the rise in the number of road traffic fatalities. According to the European Union’s report (EC 2016), 26,112 deaths and approximately 135,000 injuries were reported as a result of road traffic accidents on European roads. The age group of 15-24 years (young people) also account for almost 14% of the road fatalities across Europe. Almost half of the fatalities were among vulnerable road users like pedestrians, cyclists, and motorcyclists. Eight percent of these fatalities occurred on motorways, 37% on urban roads and the remaining 55% on rural roads. The report also describes the loss of control, over-speeding, failure to look, and poor judgment of the situation as main contributors to the crash occurrence. It is evident that all of the afore-mentioned contributing factors are human errors.

According to a National Highway Traffic Safety Administration (NHTSA) report, almost 94% of the crashes in the US were caused by driving errors. Driving errors were broadly classified into recognition errors, decision errors, performance errors, non-performance errors, and others. Statistically, recognition errors such as driver’s inattention, internal and external distractions etc., contributed to 41% of recorded crashes. Decision errors such as driving too fast for the conditions, too fast for the curves, illegal manoeuvres etc. accounted for 33% of the total crashes caused by driving errors. Eleven percent of the crashes are attributed to performance errors such as overcompensation, poor directional control etc. Non-performance attributes such as sleep accounted for 7% (NHTSA 2015).

As stated in the WHO report (WHO 2015), road infrastructures are designed primarily keeping in mind the needs of motorists, while 49% of the deaths occurred among the vulnerable road users (i.e. pedestrians, cyclists, and motorcyclists). Hence, it is important to consider all road users when designing the road infrastructure. One of the major causes of crash occurrence is over speeding (WHO 2015), which is considered as a driving error. Various studies have shown that improvements in the road design can reduce the effects of driving errors by faulty recognition and decision making, and poor control of the vehicle. Charlton (2007) for example, highlighted that the majority of the crashes occurred at the curves are caused by lack of attention, misjudgement of speed and curvature, and poor lane positioning. Various improvements in road design such as warning signs and road markings can significantly reduce speed, which in return can increase drivers' ability to control the vehicle by increasing their attention towards the hazard ahead. These road safety facts highlight the importance of considering human driving behaviour in the design process of road infrastructure.

1.2 Measures to Improve Road Safety

In order to minimize the adverse effects of road crashes on the people and the economy, various initiatives have been taken by different organizations. The World Health Organization (WHO) declared the decade 2011-2020 as a decade of action for road safety. Based on this initiative, time-based targets were established. It was decided that efforts will be made to reduce fatalities due to road accidents by half by the year 2020. Similarly, European commission set their aim towards reducing the number of fatalities due to road crashes by half in the year 2020 compared to 2010 (Commission 2010). This aim encouraged other countries to improve road safety in areas under their jurisdictions. In Flanders it was aimed to reduce road fatalities down to 200 by 2020 and further down to 133 by 2030 (Ariën 2016).

Many other countries have already set road safety as a priority. For example in the year 1997, the Road Traffic Safety Bill based on Vision Zero was passed by the Swedish Parliament. Vision Zero can be described as a philosophy that not a single person will be killed or seriously injured in a road traffic accident. The difference between other road safety systems and Vision Zero system is that in other road safety systems, road safety is considered as a responsibility of road users only whereas in the Vision Zero system, it is shared by the system designer and road user equally (Tingvall and Haworth 2000). Based on this philosophy, Sweden was among the European countries that have the least number of road fatalities in 2015 with 27 fatalities per million inhabitants (EC 2016). Another example is that of The Netherlands where the concept of sustainable safety was adopted in order to improve the road safety in the 1990s. In the concept of sustainable safety, all things are measured in regards with the road user. The meaning of this is that all aspects of the road designs e.g. traffic, road environment and the traffic rules (traffic and transport systems) etc., must be adopted according to the limitations of the human capacity. The concept of sustainable safety focuses on three design principles i.e. functionality; homogeneity; and predictability. The functionality of the system is that the actual use of the system is in compliance with the intended use. Homogeneity means that significant differences in speeds, direction, and type of road users should be avoided. If separation (in time or space) of type of road users at a certain facility is not feasible/possible, motorized vehicles are forced to reduce their speed. Predictability is defined as the road design is easier to understand to the road users and they can easily recognize what kind of driving behaviour is required. By implementing this concept rigorously, the Netherlands has become one of the countries with the best road safety records (Wegman et al. 2005). Following the idea of sustainable safety, roads in the Netherlands remain the safest in the world with 31 fatalities per million inhabitants (EC 2016). The above mentioned strategies included changes in road design accordingly. Such examples can be inspirational to policymakers in reducing the magnitude of human and financial losses resulting due to road crashes.

The above mentioned examples highlight the fact that road safety considerations in the road design are important in reducing the number of crashes. The report mentioned in the previous section provided by the National highway traffic safety administration (NHTSA) assigned 2 percent of the total crashes to the road design and atmospheric conditions. Road design, traffic signs and obstructions in vision of the drivers collectively account for approximately 15% of the crashes caused due to road design and atmospheric conditions (NHTSA 2015). The International Road Assessment Program (iRAP) devised a five-star rating model for the roads to improve the safety of the road design. According to this model, five-star roads are the safest whereas one-star roads are the least safe (iRAP 2017). The stars are assigned to the roads based on their road design. According to the World Health Organization's Global Safety Report, the star rating model when applied over 500,000 km of roads in 62 countries shows that less than 20% of the roads are three star roads for pedestrians, 50% of the roads assessed in America, Europe, and the Pacific region are three-stars for vehicle occupants, and for motorcyclists, less than 20% roads in South East Asia are three-stars or better (WHO 2015). These facts highlight that improvements in road design can significantly reduce crash occurrence and still major improvements are required in road designs so that road safety can further be improved. In this thesis, we focus on evaluating road designs in relation to the drivers behaviour. Addressing these two aspects of traffic safety will help in considerable reduction in crash occurrence.

Each modification in the road design aiming towards the prevention of road crashes has a close relation with the driving behaviour. This is because all such modifications aim towards correcting the faulty driving behaviour which contributes to the crash occurrences. Numerous examples can be found where road safety of a design can be increased by considering aspects of traffic and human driving behaviour hence, highlighting their importance in the design considerations (Sarvi et al. 2004, Alexei et al. 2005, Horberry et al. 2006, De Blasiis and Calvi 2011, Gómez et al. 2011, Montella et al. 2011, Kitamura and Yotsutsuji 2015). There are different concepts or approaches of road designs which can result in reduced crashes. Traffic conflict techniques (TCTs) and self-explaining roads (SERs) are the two of many concepts being used in road design to correct the human behaviour according to the road design hence, reducing the number of crashes. These concepts are discussed briefly in the following sections.

1.2.1 Traffic Conflict Techniques

Traffic conflicts can be defined as observational events in which two road users approach each other in space and time to such an extent that a collision will occur if their trajectories do not change (Amundsen and Hyden 1977). This definition, though recognized internationally, still has limitations as the difference between conflict and non-conflict situations remains unclear in practice (Chin and Quek 1997). Chin and Quek (1997) presented a pyramid model of conflicts based on the concept of continuity of traffic events in which accidents were placed at the top and undisturbed passages were placed at the bottom. Serious, slight and potential conflicts came after accidents in descending order.

The concept of Traffic Conflict Techniques (TCTs) is considered as a proactive approach because it analyses a safety situation from the aspect of observable traffic events other than crashes (Zheng et al. 2014). The need to proactively analyse events resulting in accidents comes from the fact that the traditional objective road safety is measured by the number of accidents reported and analysis of resulting fatalities and injuries (Archer and Kosonen 2000). However, the problem with the traditional technique is that accidents are rare occurrences and not all accidents are reported. Moreover, the behavioural and situational aspects of the events are usually not mentioned in the police report (Iasmin et al. 2016). Hence, this concept has a potential to increase the road safety of a design at planning stage.

Moreover, the probability of occurrence of conflicts in traffic is higher than the probability of accidents as shown in the Figure 1-1. Decreasing probabilities of conflicts can ultimately result in a decrease in the crash count. Traditional indicators such as traffic volume, average annual daily traffic etc. do not estimate the reasons or severity of the conflicts. To estimate the type of conflicts, various indicators called proximal surrogate safety indicators are used. These are described in the next section.

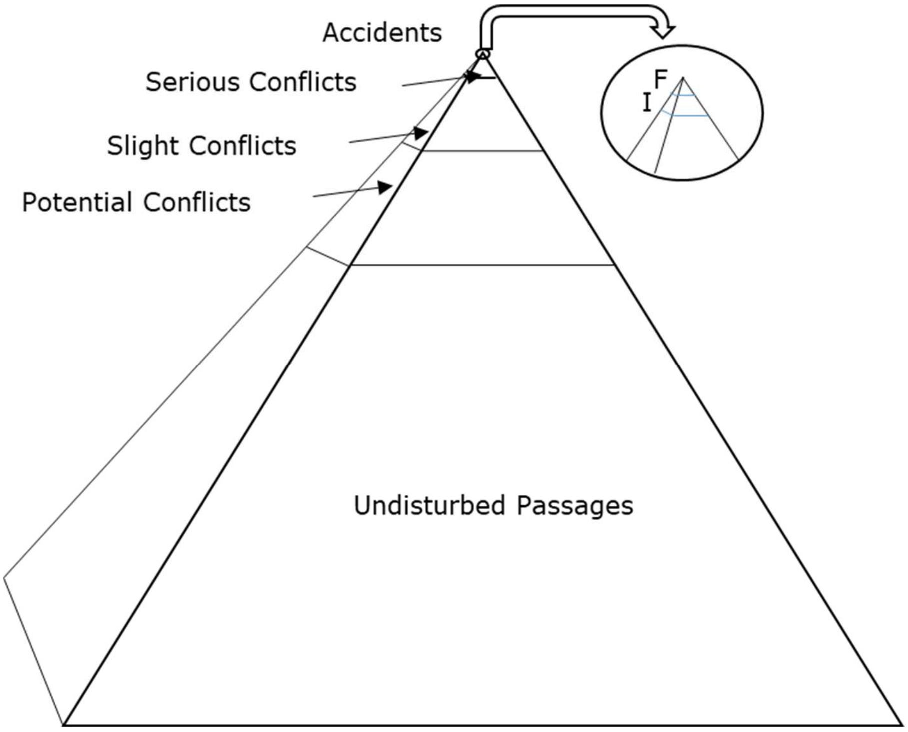


Figure 1-1: The relation between severity and frequency of elementary events in traffic by a safety pyramid (Laureshyn et al. 2010)

1.2.2 Surrogate Safety Indicators

During previous decades, considerable research has been conducted on the development of surrogate safety indicators (Parker Jr and Zegeer 1989, Lord and Mannering 2010, Savolainen et al. 2011, Zheng et al. 2014). Mahmud et al. (2017) reviewed proximal surrogate safety indicators in detail and divided them into two groups namely temporal and non-temporal. Non-temporal indicators were further divided into three categories based on measuring attributes such as distance, deceleration and others. It is important that appropriate proximal safety indicators should be selected for assessing the road safety of a particular section. To do so, the type of conflicts that can occur at the road section under consideration should be estimated correctly. For example, the parameter "time to collision" (TTC) is useful for prediction of rear end, turning or weaving, collision with a stationary object (i.e. parked vehicle), crossing vehicles and pedestrians. The parameter post encroachment time (PET) is useful mainly in predicting right angle or crossing crashes with vehicles and pedestrians. The detailed list is provided in the study of Mahmud et al. (2017). In order to assess the safety of a road section, using a combination of proximal safety indicators is recommended (Mahmud et al. 2017). However, Laureshyn et al. (2010) proposed that it is important to keep the number of indicators to a minimum as too many indicators will cause difficulty in making the method operational.

Data collection of these indicators can be conducted using various techniques. These techniques include data collection at the site, analysis of video recordings recorded from the site, and computer simulation (micro-simulation) models. The first two techniques i.e. manual data collection from the site and video recording analysis can be done during or after the construction of a road design. Micro-simulations, on the other hand, can be used to collect data before the project has been executed in the real world. As the objective of this thesis is to improve the safety evaluation at the design phase before execution of the project, micro-simulation is discussed in Section 1.2.6 of this chapter.

1.2.3 Self – Explaining Roads

In the concept of self-explaining roads, the driver is encouraged to naturally adopt behaviour consistent with design and function (Theeuwes and Godthelp 1995, Theeuwes 1998). The concept aims towards distinctive classification of different classes of roads. Within each class, road design features such as carriageway width, road markings, signing, and lighting are made consistent throughout the road length. This makes the roads classes easy to be distinguished and drivers after road class recognition can easily adopt their behaviour accordingly. The environment can effectively provide a "label" for the particular class of road (motorway, rural, urban etc.,) and there would thus be less need for additional traffic control devices such as traffic signs to regulate traffic behaviour (European Commission 8 October 2018).

Different types of road marking treatments have been studied to have positive impacts on driving behaviour such as decrease in longitudinal speed and on lateral position etc, (Davidse et al. 2004, Alexei et al. 2005, Herrstedt 2006, Charlton 2007, Coutton-Jean et al. 2009, Ding et al. 2013, Ariën et al. 2017). Application of such treatments is important in evoking correct driving behaviour in the drivers at various road sections such as curves, intersections, rural-urban transitions etc. As explained earlier that over – speeding is one of the major contributors in crash occurrence (EC 2016), objective of majority of the road marking treatments is to make drivers reduce their speed. To make sure that the proposed changes in the road marking treatments will effectively achieve the required results, it is important to evaluate the proposed changes with respect to driver capabilities and capacities. To do so, driving simulator is a safe and effective tool and is being used for studying different new alternative designs and their effects on driving behaviour.

It is important that road safety is integrated into the road design procedure in initial planning stages of the project. In this way, it can be predicted proactively whether the proposed design will be able to evoke the correct driving behaviour in the drivers which will ultimately result in reduction in number of crashes. To evaluate the road safety of an infrastructure design, road safety impact assessment (RSIA) and road safety audits (RSAs) are carried out. RSIAs are focused mainly at strategic levels of the road network whereas RSAs are focused mainly on the project level. Details of the procedures usually followed for conducting RSIA and RSA and considerations taken into account while doing so are provided in the following sections.

1.2.4 Road safety impact assessment (RSIA)

The European Union Directive 2008/96/EC defines road safety impact assessment as "*a strategic comparative analysis of the impact of a new road or a substantial modification to the existing network on the safety performance of the road network*"(European Parliament and Council 2008). According to the EU directive, all member states of the European Union are responsible to develop guidelines for conducting RSIA so that the road safety of the EU road network can be improved. As a result, various EU countries developed their guidelines for RSIA (Pokorný and

Hrubý 2010). Annex I of the EU directive mentioned above states that RSIA should be carried out for all infrastructure projects belonging to the Trans European road network (TEN) in the initial planning and design phase of the project. Preferably, RSIA should be prepared in parallel to the strategic feasibility studies. In this way, a RSIA report can be formulated without causing much delays in the project duration. A separate team is required to be formulated for conducting RSIA. The qualifications and job descriptions of the RSIA team members are provided in the EU directive. The same team might also be used for conducting RSA in later stages of the project. The results of RSIA studies should improve the quality of the feasibility study and decision making by providing necessary road safety information and cost-benefit analysis of the alternative solutions assessed in RSIA report (Laurinavičius et al. 2012). A flow chart of key procedures involved in a RSIA process is presented in Figure 1-2. As RSIA has wider scope, micro-simulation study is considered to be the most suitable tool as it can help the RSIA team in predicting zones with possible risks to the road safety. Micro – simulation is discussed briefly in the Section 1.2.6 of this chapter.

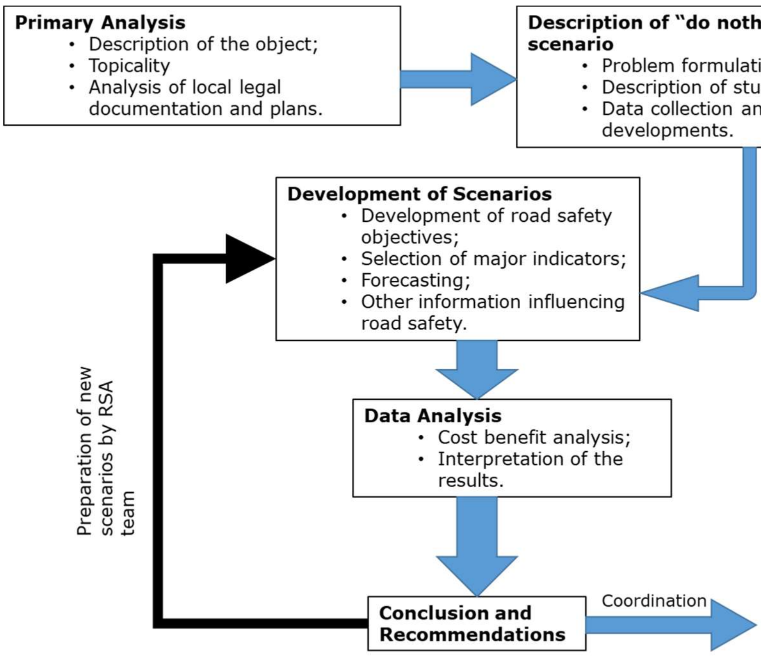


Figure 1-2: Flow Chart of Key Procedures In RSIA (Laurinavičius et al. 2012)

1.2.5 Road safety audit (RSA)

European Union directive 2008/96/EC defines road safety audit as "*an independent detailed systematic and technical safety check relating to the design characteristics of a road infrastructure project and covering all stages from planning to early operation*"(European Parliament and Council 2008). In Annex II of EU directive 2008/96/EC, criteria for carrying out road safety audits (RSA) at four different stages of a road infrastructure project is provided. These four stages are:

- At preliminary draft design stage;
- At detailed design stage;
- At pre-opening stage;
- During Early operation: assessment of road safety in the light of actual behaviour of users.

This means that a RSA needs to be carried out twice before the beginning of the execution of the project. In this way, RSAs can considerably improve the safety aspects of the project. Especially the stages before the start of the execution are important in the scope of this thesis as this thesis aims towards safety evaluation of infrastructure designs before they are implemented in the real world. Criteria mentioned in the above mentioned EU directive for preliminary draft design stage and detailed design stage are presented in Table 1-1.

Table 1-1: Criteria for preliminary design stage and detailed design stage for RSA

	Preliminary Draft Design Stage	**Detailed Design Stage**
1	Geographical location of the project (e.g. areas prone to landslides, flooding, avalanches, seasonal and climatic conditions, and seismic activity).	Layout.
2	Types of junctions and distance between junctions.	Coherent road signs and markings.
3	Number and type of lanes.	Lighting of lit roads and intersections.
4	Types of road users allowed on the new road.	Roadside equipment

5	Functionality of the road in the network.	Roadside environment including vegetation
6	Meteorological conditions.	Fixed obstacles at the roadside.
7	Driving speeds.	Provision of safe parking areas.
8	Cross-sections (e.g. width of carriageway, cycle tracks, foot paths).	Vulnerable road users (e.g. pedestrians, cyclists, motorcyclists).
9	Horizontal and vertical alignments.	User-friendly adaptation of road restraint systems (central reservations and crash barriers to prevent hazards to vulnerable users).
10	Visibility.	
11	Junctions layout.	
12	Public transport and infrastructures.	
13	Road/rail level crossings.	

Based on the points mentioned in Table 1-1, detailed guidelines are established by EU countries in the form of a checklist which helps the auditing team examine infrastructure projects based on the above mentioned elements in a variety of aspects. However, these points mainly focus on the design parameters. Usual procedures to carryout RSAs include site visits and personal perception of the road safety auditor as described in various RSA procedures (Petr Pokorný 2008, Transport Malta 2011, Lech Michalski 2013). It is possible that few elements of the road design do not perform efficiently and safely under various road conditions. Such elements can cause faulty human behaviour and might get overlooked or ignored in the audit process due to complete reliance on personal abilities of the auditors (Lee et al. 2011). Various studies have identified that different conditions can have adverse effects on driving behaviour and those adverse effects can be minimized by improving the road design. For example, De Blasiis and Calvi (2011) studied the effects of various traffic intensities in the main freeway on the merging length of the drivers in the acceleration lane. The study concluded that the traffic volume is directly proportional to the merging length (i.e. merging length increases with increase in traffic volume).

Besides various design components, various traffic situations have also been found to affect the driving behaviour adversely if current road design does not cope with such problematic situations. For example, Moridpour et al. (2015) studied impacts of heavy vehicles on the traffic stream. They found that the presence of heavy vehicles can increase the number of lane changing manoeuvers. This can increase the probability of accident occurrence as the number of conflict points increases due to an increase in lane changing manoeuvres.

For RSA to be conducted before the construction of the project, driving simulator can be used so that the resulting road design has increased safety standards. However, similar to the road design process, road safety audit process relies on existing standards which might not take recent developments into the account. Reliance on standards is not necessarily a bad practice. However, simplification of knowledge to simple values and tables if not done properly without recognizing the nature of the driving tasks can result into risk abundant designs due to selection of the standard values (Santiago-Chaparro et al. 2011). Europe's road infrastructure safety management consider pro-active evaluation of the road designs as a foundational aspect in improving road safety standards (Parliament and Union. 2008). When driving simulator is used for RSA, it is called virtual road safety audit (VRSA). A brief explanation of VRSA is provided in Section 1.2.7 of this chapter.

Therefore, it is important to analyse the alternate design solutions. Various techniques are used for analysing the new alternative designs which have not been yet constructed. These techniques include micro-simulation and driving simulation. Micro simulation provides data for various surrogate safety measures which are then analysed to study the effects of different traffic conditions such as traffic volume, traffic composition (percentages of passenger and heavy vehicles) on various design measures. Driving simulation is used to study the impacts of various road environments and traffic situations on the driving behaviour. In the next section, a brief overview of micro-simulation is provided. To study the effects of various road designs on driving behaviour, driving simulation has emerged as a useful tool in understanding and analyse the human factors involved in the driving task. It is a safe and effective way to study the interaction between drivers and the road environment. The next section describes the use of driving simulators in the RSA process.

1.2.6 Micro Simulation

Due to advancements in the field of computers, it has become possible to create various traffic simulation models that can graphically present the traffic travelling on a particular road network. Various mathematical models have been developed by traffic engineers to represent the traffic behaviour and interaction of traffic users among themselves and with the environment. These mathematical models serve as guidelines to the computer engineers and experts to create traffic simulations. The idea behind traffic simulation is to predict differences in various behavioural attributes of vehicles in a traffic stream. Inputs for microsimulations are usually the traffic volume (number of vehicles), road design and traffic control devices (traffic lights, speed limits). Based on these inputs, trajectories for each individual vehicle are calculated. After the trajectories of each individual vehicle is calculated, areas prone to conflicts are separated on the basis of conflict severity i.e. serious, slight, potential etc.

There are number of micro-simulation programs available nowadays in which various models are included such as car following model, gap acceptance, etc. These simulation programs help traffic engineers in predicting trajectories of vehicles on the road network before it is built in the real world. From these trajectories, number and nature of possible conflicts can be calculated and their causes can be highlighted. PTV (VISSIM), TSS (AIMSUN), Quadstone (Paramics), and Rioux Engineering Texas are some examples of micro simulation programs used to predict vehicle trajectories on the road network. The Federal Highway Authority has developed a separate tool (with the assistance of the above mentioned software developers) which calculates the number and type of conflicts that can occur resulting from the predicted trajectories of the simulated traffic. This tool is called surrogate safety assessment model (SSAM) and considers time to collision (TTC) and post encroachment time (PET) (Model 2008).

There are other examples of micro-simulation programs in which various models for driving behaviour are developed. For example, a HUTSIM micro simulator developed at Helsinki University of Technology provides high fidelity for traffic networks, and dynamic interactions between road-users and traffic environment (Archer and Kosonen 2000). Another micro-simulator program called AIMSUN is based on an important behavioural parameter, the driver's reaction time (Barceló Bugeda et al. 2003). Hence, the selection of the micro-simulator program depends on the type of surrogate safety measures for which data is required.

From the surrogate safety parameters mentioned in the previous section, it is evident that the safety parameters, which are considered in micro-simulation consider driving behaviour in terms of speed adaptation models, car following and lane changing models etc. The models used in micro-simulation provide data obtained from the calculations based on the algorithm designed based on the previous research. Micro-simulation does not involves the actual drivers in the process. Hence, a realistic driving behaviour for these parameters on individual level and data for other factors of human driving behaviour such as human interaction with the road design, cognitive abilities and human capacities etc., cannot be collected using micro-simulations. In this view, driving simulators are great tools to fully take human driving behaviour into account.

1.2.7 Virtual Road Safety Audit (VRSA)

A road safety audit (RSA) carried out using a driving simulator as an assessment tool is called a "Virtual Road Safety Audit (VRSA)", a term used by Santiago-Chaparro et al. (2011). The main difference between a traditional RSA and a VRSA is that in a VRSA, the design is assessed based on variables defining human behaviour. Although there are proximal surrogate safety variables, such as discussed in previous section, which can be considered to represent certain aspects of human behaviour, the variables considered in a VRSA are mainly centred around the individual behaviour of the drivers.

Variables such as mean speed, acceleration/deceleration, lateral position etc., represent the driving behaviour realistically when collected from driving simulator. However, consideration of these variables as indicators of driving behaviour is dependent on the type of road design which needs to be investigated. Ariën et al. (2017) studied the effects of various pavement markings at curves on mean speed, mean acceleration/deceleration, mean lateral position and standard deviation of lateral position (SDLP). Charlton (2007) compared the effects of advance warning, delineators and road marking treatments by considering mean speed and lateral displacement (lateral position) variables to study the role of attention while driving curves. Hence, it highly depends on the researcher to consider appropriate driving behaviour variables with respect to the type of road design in order to evaluate the traffic safety of that road design.

Moreover, the data for various proximal safety measures such as time to collision (TTC), post encroachment time (PET) etc., can also be collected using driving simulators. For example Yan et al. (2008) conducted a driving simulator validation study by collecting data for speed and crash history (safety measure). The study concluded that a driving simulator is valid for studying driving behaviour at signalized intersections in absolute manner in terms of speed whereas validity was relative in case of rear-end crashes at right turns at the intersection.

Defining variables with which a driving behaviour can be evaluated depends highly on the type of the methodology selected and the research question, which is being studied. For certain research questions, these variables can also determine whether additional hardware is required or not. For example, various research questions such as the comprehension of road signs require recording the eye movements of the driver so that they can notice the stimuli in time in order to make appropriate decisions. This requires an eye tracking device to be included with the driving simulator hardware. There are various examples in which the methodology adopted to address a specific question that required the use of eye tracker (Salvucci and Liu 2002, Pradhan et al. 2005, Pollatsek et al. 2006, Fisher et al. 2007, Palinko et al. 2010). For instance, Gómez et al. (2011) used the eye tracking device to examine whether drivers fixate their eyes on particular areas of the field of vision in order to make correct decisions while studying the effects of advanced yield markings. Ariën et al. (2013) in a driving simulator study used eye tracking to validate the position of work zone related route diversion signs. In this study, the number of glances on both permanent and temporary work zone related sign boards and behavioural outcomes in terms of lane changes and speed choice were calculated and analysed.

As mentioned in previous sections that to carry out RSAs, a special team consisting of experts in other fields than road design is prepared. The addition of a driving simulator team (which includes 3D modelling experts, IT professionals, human factors experts, etc.) can help in running the driving simulator studies parallel to the other design processes. In this way, innovative alternative designs for which past data is not available, can be tested with the driving simulator. The fact that a driving simulator provides empirical data for the variables (for which previous data does not exist) can help road designers better understand different design aspects with respect to the driving behaviour. The scenario creation process and experimentation of the driving simulator studies may require considerable time considerations and may cause delays in RSA report. However, the results and recommendations of the driving simulator studies might point out timely improvements in the road design which can save precious time, resources and most importantly can save lives due to the avoided crashes in the later stages of the project.

The added value of the driving simulator in the RSA process is that it helps the road safety auditor to analyse the design based on human behaviour. It is recommended by the European commission that all stake holders including the end road users should be included in the safety evaluation of a new road design (European Parliament and Council 2008). This is one of the most useful advantages of driving simulators that it helps in evaluating the perceived/subjective safety by allowing the end road user to experience the road design before it is built and provide feedback about it. Hence, the purpose of VRSA is not to replace the existing RSA methods rather to assist the existing RSA methods in consideration of human behaviour.

The identified knowledge gaps from the reviewed literature are

- The road design and road safety evaluation procedures do not emphasise enough the behaviour of end road users in the design process and their safety evaluation.
- Inclusion of the end road users in a direct way in road design and safety evaluation processes needs further exploration.
- Alternate road designs are needed to be explored in a proactive way for improving safety standards.

1.3 Objectives

In general, the motivation for this thesis is to highlight the importance of human driving behaviour and its inclusion into the road design process. Based on human driving behaviour, the safety of road designs should also be evaluated. The use of driving simulators for research purposes is gaining popularity as it enables researchers to study human driving behaviour to a greater extent than micro-simulation. Based on the extensive literature review and the knowledge gaps identified, the general objectives of this thesis are

- To investigate the usefulness of driving simulation for the evaluation of road designs prior to their construction;
- To investigate the usefulness of driving simulation for the evaluation of road designs on the basis of human factors.

Fulfilling these objectives will help in achieving a better road designs afterwards and as a consequence to improve road safety of the new road designs.

More specifically in this PhD, three case studies were selected to evaluate the effects of different infrastructural designs on the driving behaviour on two different road categories: a two-way rural road, and freeways (motorways). All of the three selected case studies share a common central theme that is the presence of discontinuities in the road design and it is known that discontinuities are known to create sudden changes in driving behaviour (deceleration, lane changing, etc.) if not appropriately designed.

The discontinuities are the merging of two freeways, the separation of local and express traffic, and the presence of sharp horizontal curves in the road network. All of them have the potential to create risky driving behaviour if not carefully designed. The motivation to select these studies comes from the current problems being faced by the local road authorities in Belgium and Netherlands. In this thesis, we are looking for improvements that can be influential in make the road designs more 'self-explaining' to the drivers. These case studies were empirical and exploratory in nature and a comparison of driving simulator results with field data was not made because in new road designs, these data are simply not available. Moreover in all three studies, methodology was designed to evaluate the road designs from the perspective of car drivers. The results of empirical case studies carried out in this thesis will help the designers and the policy makers foresee the possible effects of the different designs on driving behaviour if implemented in real life.

1.4 Thesis Outline

In the second chapter (Chapter 2), detailed discussion on the driving simulators is provided. The purpose of including this discussion in this thesis and dedicating a separate chapter is to highlight the usefulness of driving simulator for similar research. Different varieties of driving simulator based on their physical appearance and the driving environment they provide to the drivers are discussed in this chapter. Steps involved in scenario creation process and considerations of various elements in designing effective methodology are discussed. The type of driving simulator hardware and the driving simulator program used in all three studies conducted for this research is also explained in this chapter.

The first case study (Chapter 3) in this thesis addresses the effects on driving behaviour and safety in a driving simulator of various soft separation methods used to separate express and local lanes. The motivation for using soft separation methods comes from the problem reported by the Dutch road authority. They have used hard separations for separating express and local lanes, and where blockage of express lanes in some cases resulted in lengthy congestions and tiresome traffic jams. Because of the hard separation, the traffic on express lanes cannot be diverted as there is no escape route. Instead, soft separation can potentially solve this problem as an escape route for the traffic on express lanes can easily be provided. However, it is important to avoid lane changing manoeuvers from express to local lanes and vice versa unless it is allowed by road authorities. To accomplish this, a driving simulator study was designed and different soft separation methods, i.e. tubular delineators, a vegetation strip, a closed double line, and a cross hatch marking were used to separate express and local lanes. Drivers' crossing behaviour in the simulator and reported temptations to cross were analysed to see possible effects of soft separations on drivers when stuck in a traffic jam on express lanes without any escape route.

In the second case study (Chapter 4), we focused on merging of freeways with a decreasing number of lanes according to the Dutch Road Standards. Dutch standards provide various merging freeway designs with decreasing number of lanes applicable when the converging angle between the two freeways is small. Dutch standards also mention which type of design is not preferred . Indeed, the taper design is not preferred and the guidelines require strong arguments from the designer to support its use. The Dutch guidelines however do not provide clear reasons why they choose the taper design is to be the least favourite design option. In fact, a recent simulation study from Ruyter (2016) in the Netherlands even showed that a taper design in some cases can be a good option. This motivated us to design a driving simulator study in which a comparison among the two designs (the most preferable standard design and the least preferable taper design) was carried out. The objective of the study was to compare the safety of the two merging designs based on human driving behaviour and their compliance with the sustainable safety and self – explaining road designs in different traffic compositions and identify the reasons which make a design preferable.

In the third and the last case study of this thesis (Chapter 5), we focus on correction of driving behaviour at horizontal curves. As a significant portion of crashes occurs at horizontal curves. The probability of occurrence of a fatal crash is 1.5 to 4 times higher in horizontal curve section than a tangent section (Glennon et al. 1983). Previous studies show that correcting human driving behaviour can result in crash reduction at curves (Charlton 2007, Calvi 2015, Montella et al. 2015). As mentioned in the previous section (paragraph 1.1), 55% of the crashes occur on rural roads in Europe (EC 2016). Therefore, we selected two real world horizontal curves and replicated them in a driving simulator environment. Two road markings, optical circles and a herringbone pattern, were applied before and in the horizontal curve to evaluate the effect on two driving behaviour parameters i.e. speed and lateral position. The motivation for the use of optical circles came from the fact that various road treatments are known to cause speed reduction due to increased perceived speed (Meyer 1999, Rosey et al. 2008, Ding et al. 2013). Optical circles were designed on the same principal so that the perceived speed is higher than the actual speed which ultimately results in a decrease in actual speed hence, were applied before the curve. Optical circles have not been applied before the horizontal curves previously both in the field and in the driving simulator. The herringbone pattern was designed to correct the driving behaviour through the curve by providing the most flattened trajectory through the curve. The objective of this study was to provide designers with the most suitable low cost solution to modify driving behaviour at curves.

In the last chapter (Chapter 6), conclusions and policy implications are provided based on the results of the three driving simulator case studies. Overall achievement of the general objectives of the research is discussed. Topics for future research are also included in the last chapter. The implications can be helpful for road designers and for policy makers in improving the safety of road designs. The chapter also puts emphasis on the use of driving simulators to evaluate safety of the road designs based on human driving behaviour in planning stages of the project (i.e. before it is built in the real world). Limitations of the study such as assumptions made, limitations in scenario design, and type of road user focused in this thesis are discussed in the last part of this Chapter.

1.5 References

Alexei, R. T., et al. (2005). Safety impact of edge lines on rural two-lane highways.

Amundsen, F. and C. Hyden (1977). The Swedish traffic conflict technique. Proceedings of First Workshop on Traffic Conflicts, Institute of Transport Economics, Oslo.

Archer, J. and I. Kosonen (2000). The potential of micro-simulation modelling in relation to traffic safety assessment. Proceedings of the ESS Conference, Citeseer.

Ariën, C. (2016). The effects in distance and time of traffic calming measures near road transitions and discontinuities by means of driving simulator research.

Ariën, C., et al. (2017). "The effect of pavement markings on driving behaviour in curves: a simulator study." Ergonomics **60**(5): 701-713.

Ariën, C., et al. (2013). Ex-ante evaluatie van wegsignalisatie met een rijsimulator.

Barceló Bugeda, J., et al. (2003). Safety indicators for microsimulation-based assessments. Transportation Research Board 82nd Annual Meeting, TRB.

Calvi, A. (2015). "A study on driving performance along horizontal curves of rural roads." Journal of Transportation Safety & Security **7**(3): 243-267.

Charlton, S. G. (2007). "The role of attention in horizontal curves: a comparison of advance warning, delineation, and road marking treatments." Accid Anal Prev **39**(5): 873-885.

Chin, H.-C. and S.-T. Quek (1997). "Measurement of traffic conflicts." Safety science **26**(3): 169-185.

Commission, E. (2010). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Towards a European road safety area: policy orientations on road safety 2011-2020. Brussels, European Commission.

Coutton-Jean, C., et al. (2009). "The role of edge lines in curve driving." Transportation Research Part F: Traffic Psychology and Behaviour **12**(6): 483-493.

Davidse, R., et al. (2004). "The effect of altered road markings on speed and lateral position." SWOV Institute for Road Safety Research, The Netherlands.

De Blasiis, M. R. and A. Calvi (2011). "Driver Behavior on Acceleration Lanes." Transportation Research Record: Journal of the Transportation Research Board **2248**(-1): 96-103.

Ding, H., et al. (2013). "Experimental research on the effectiveness of speed reduction markings based on driving simulation: A case study." Accident Analysis & Prevention **60**: 211-218.

EC (2016). Road Safety in the European Union: Trends, Statistics and Main Challenges. Brussels, Mobility and Transport DG.

European Commission (8 October 2018). "Self explaining roads." from https://ec.europa.eu/transport/road_safety/specialist/knowledge/road/designing_for_road_function/self_explaining_roads_en.

European Parliament and Council (2008). "Directive 2008/96/CE on road infrastructure safety management." Official Journal of the European Union.

Fisher, D. L., et al. (2007). "Empirical evaluation of hazard anticipation behaviors in the field and on driving simulator using eye tracker." Transportation Research Record **2018**(1): 80-86.

Glennon, J. C., et al. (1983). Safety and operational considerations for design of rural highways curves, Final Report.

Gómez, R., et al. (2011). "Do advance yield markings increase safe driver behaviors at unsignalized, marked midblock crosswalks? Driving simulator study." Transportation Research Record: Journal of the Transportation Research Board(2264): 27-33.

Herrstedt, L. (2006). Self-explaining and Forgiving Roads–Speed management in rural areas. ARRB Conference.

Horberry, T., et al. (2006). "The possible safety benefits of enhanced road markings: A driving simulator evaluation." Transportation Research Part F: Traffic Psychology and Behaviour **9**(1): 77-87.

Iasmin, H., et al. (2016). "Safety effectiveness of pavement design treatment at intersections: Left turning vehicles and pedestrians on crosswalks." IATSS research **40**(1): 47-55.

iRAP (2017). "iRAP Methodology fact sheets." from https://www.youtube.com/watch?v=wX459mg_0YE.

Kitamura, K. and H. Yotsutsuji (2015). "An Experimental Study on the Effect of Sequential Transverse and Lateral Markings on Perceived Speed on a Single-lane Straight Road." Journal of Ergonomics **3**: 2.

Laureshyn, A., et al. (2010). "Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation." Accident Analysis & Prevention **42**(6): 1637-1646.

Laurinavičius, A., et al. (2012). "Policy instruments for managing EU road safety targets: road safety impact assessment." The baltic journal of road and bridge engineering **7**(1): 60-67.

Lech Michalski, K. J., Joanna Zukowska (2013). Un decade of action for road safety in the national road safety strategy until 2020 – Polish approach. 16th Road Safety on Four Continents Conference. Beigning, China.

Lee, J., et al. (2011). "Matching simulator characteristics to highway design problems." Transportation Research Record: Journal of the Transportation Research Board(2248): 53-60.

Lord, D. and F. Mannering (2010). "The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives." Transportation Research Part A: Policy and Practice **44**(5): 291-305.

Mahmud, S. S., et al. (2017). "Application of proximal surrogate indicators for safety evaluation: a review of recent developments and research needs." IATSS research.

Meyer, E. (1999). "Application of Optical Speed Bars to Highway Work Zones." Transportation Research Record **1657**: 48-54.

Model, F. S. S. A. (2008). Validation: Final Report. Publication No, FHWA-HRT-08-051. Washington, DC.

Montella, A., et al. (2011). "Simulator evaluation of drivers' speed, deceleration and lateral position at rural intersections in relation to different perceptual cues." Accident Analysis & Prevention **43**(6): 2072-2084.

Montella, A., et al. (2015). "Effects of traffic control devices on rural curve driving behavior." Transportation Research Record: Journal of the Transportation Research Board(2492): 10-22.

Moridpour, S., et al. (2015). "Impact of heavy vehicles on surrounding traffic characteristics." Journal of advanced transportation **49**(4): 535-552.

NHTSA (2015). Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey, National Highway Traffic Safety Administration.

Palinko, O., et al. (2010). Estimating cognitive load using remote eye tracking in a driving simulator. Proceedings of the 2010 symposium on eye-tracking research & applications, ACM.

Parker Jr, M. and C. V. Zegeer (1989). Traffic conflict techniques for safety and operations: Observers manual, United States. Federal Highway Administration.

Parliament, E. and C. o. t. E. Union. (2008). "Directive 2008/96/EC of the European Parliament and of the Council of 19 November 2008 on Road Infrastructure Safety Management." Official Journal of the European Union.

Petr Pokorný (2008). Road Safety Audit in the Czech Republic. 21st ICTCT, Riga-Latvia.

Pokorný, P. and Z. Hrubý (2010). "Implementation of road safety audit and inspection in the Czech Republic." Advances in transportation studies(22).

Pollatsek, A., et al. (2006). "Using eye movements to evaluate a PC-based risk awareness and perception training program on a driving simulator." Human factors **48**(3): 447-464.

Pradhan, A. K., et al. (2005). "Using eye movements to evaluate effects of driver age on risk perception in a driving simulator." Human factors **47**(4): 840-852.

Rosey, F., et al. (2008). "Impact of perceptual treatments on lateral control during driving on crest vertical curves: a driving simulator study." Accid Anal Prev **40**(4): 1513-1523.

Ruyter, M. d. (2016). The road safety of merging tapers: Measuring the effect of varying geometric designs and traffic conditions on driving behaviour at merging tapers. Civil Engineering. Delft, TU Delft. Masters.

Salvucci, D. D. and A. Liu (2002). "The time course of a lane change: Driver control and eye-movement behavior." Transportation Research Part F: Traffic Psychology and Behaviour **5**(2): 123-132.

Santiago-Chaparro, K., et al. (2011). Virtual Road Safety Audits Using Driving Simulators: A Framework. 3rd International Conference on Road Safety and Simulation.

Sarvi, M., et al. (2004). "Freeway ramp merging phenomena in congested traffic using simulation combined with a driving simulator." Computer-Aided Civil and Infrastructure Engineering **19**(5): 351-363.

Savolainen, P. T., et al. (2011). "The statistical analysis of highway crash-injury severities: a review and assessment of methodological alternatives." Accident Analysis & Prevention **43**(5): 1666-1676.

Theeuwes, J. (1998). "Self-explaining roads: Subjective categorisation of road environments." Vision in vehicles **6**: 279-287.

Theeuwes, J. and H. Godthelp (1995). "Self-explaining roads." Safety science **19**(2): 217-225.

Tingvall, C. and N. Haworth (2000). Vision Zero: an ethical approach to safety and mobility. 6th ITE International Conference Road Safety & Traffic Enforcement: Beyond.

Transport Malta (2011). Technical Guidelines for the Preparation of Road Safety Audits, Road Safety Impact Assessments and Road Safety Inspections. T. Malta.

Wegman, F., et al. (2005). Sustainable Safety in the Netherlands: the vision, the implementation and the safety effects, SWOV.

WHO (2015). Global status report on road safety 2015, World Health Organization.

Yan, X., et al. (2008). "Validating a driving simulator using surrogate safety measures." Accident Analysis & Prevention **40**(1): 274-288.

Zheng, L., et al. (2014). "Traffic conflict techniques for road safety analysis: open questions and some insights." Canadian journal of civil engineering **41**(7): 633-641.

2 Driving Simulators

2.1 Introduction

Driving simulators have become a very popular tool in studying different aspects of human driving behaviour. Applicability of driving simulators in various fields enable them to be used by the researchers such as psychologists, medical doctors and practitioners, and engineers. According to a study sponsored by The Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), and National Cooperative Highway Research Program (NCHRP), driving simulators are a useful tool in road design and their inclusion in road design process is recommended (Keith et al. 2005). Technological advancements in the field of computers have made it possible for the road designers to study different aspects of road design alternatives before they are implemented in the real world. This enables road designers to investigate the possible effects of alternative designs on the driving behaviour by analysing whether the proposed design alternatives are able to evoke correct driving behaviour from the drivers. One of the advantages of the driving simulators is that data can also be collected for dangerous situations and participants can be exposed to dangerous situations without any physical damages. Hence, a medium fidelity driving simulator was used in all of the three studies conducted in this thesis. A brief introduction of driving simulators is provided in the next section. The advantages of driving simulators along with their limitations are described in the following sections.

2.2 Composition of Driving Simulators

A driving simulator is used to mimic driving experience in a virtual world. Basically, a driving simulator is a computer system that allows users to create their customized virtual environment to drive in. We can think of driving simulator programs as a flexible framework in which all elements of different driving environments can be inserted. The steps involved in the creation of a virtual environment are discussed in section 2.5.

A driving simulator program can be run on simple configurations like a desktop PC or a laptop. Different processes such as simulation processing, data base processing, and vehicle motions run in the central processing unit (CPU) of the computer. From CPU, various sensory feedbacks such as visual or oral are generated. These feedbacks are presented through other devices such as desktop monitors, overhead projectors etc. Human responses towards these generated feedbacks are recorded through various sensors by CPU and changes are applied accordingly to the simulation. This whole driving simulation process runs in a closed loop and data is collected simultaneously and continuously. This whole process is shown in the Figure 2-1 (Fisher et al. 2011). Various other hardware devices can also be attached with the CPU to give drivers a realistic driving experience. These other hardware devices comprise a wide range of input and output devices. Input devices include a simple computer keyboard, a gaming console controller, a separate steering wheel and foot pedals (for steering car controls like braking, acceleration etc.), separate gear box to shift gears (for manual drive). Besides these input devices, to study physical conditions of the drivers during driving such as eye movements, facial expressions, anxiety etc., and many other auxiliary devices can also be attached. The most commonly used device is an eye tracker, which records eye and facial movements of the drivers. Output devices include a single desktop monitor (simple or LCD), a head mounted display (usually for Virtual reality), multiple desktop monitors (usually three LCD monitors) synchronized to produce a single image of wider vision, the use of multiple projectors projecting a synchronized image on the screen (flat or curved) placed in front of the driver, and speakers to produce sounds of the driving environment. Along with these output devices, several other devices can also be attached with the main computer to produce different other elements of the driving experience for example forces experienced by the driver in the real world (braking, acceleration, centrifugal forces at curves etc.). To make driving experience in the simulator realistic, various vibrating devices can also be attached to the base to produce vibrations due to engine, road friction and uneven terrain etc.

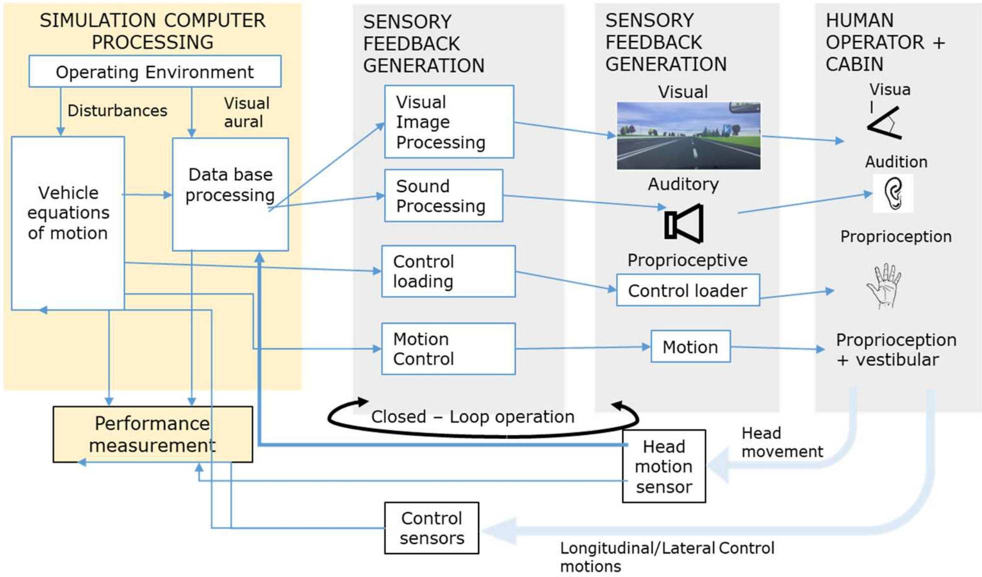


Figure 2-1: Functional elements of driving simulation (fisher et al. 2011)

2.3 Driving Simulators Fidelity

Different combinations of input and output devices and processing capacity of the main computer can be selected to create a driving simulator. However, this selection can significantly affect the degree of realism or fidelity of a driving simulator can provide.

It is important to understand the concept of fidelity of the driving simulators to make sure that the data from the driving simulator is valid. Fidelity of a driving simulator can be defined as the extent of realistic driving behaviour a driving simulator can provide (J.C.F de Winter et al. 2007). Different types of fidelity are found in the literature. Examples are physical, objective, perceptual, behavioural, functional, attribute, abstract, psychological, and concrete fidelity (Roza 2004, Lee et al. 2011). Physical fidelity of a driving simulator is the extent up to which driving simulator produces physical reality for example layout, dynamic characteristics or visual displays correspondence with on – road vehicle. Behavioural fidelity is the extent to which drivers perform in the same manner as they do on the real road(Godley et al. 2002, Mullen et al. 2010, Klüver et al. 2016). Increasing the fidelity of the driving simulator increases the validity and authenticity of the data but at the same time, increases the cost of the driving simulator.

The concepts of absolute and relative fidelities are very important to understand. This is because these two are related with the reliability of the data obtained from the driving simulator and we find them worth mentioning.

Absolute validity is established when dependent variables such as driving parameters, psychophysiological measures, or subjective evaluation take on the same numerical value as in real life. Relative validity corresponds to the coherence between effects of different variations in the driving situation (Törnros 1998, Godley et al. 2002, Mullen et al. 2010, Klüver et al. 2016).

It is very important for a driving simulator to be a useful tool for research purposes that its relative validity is satisfactory i.e. same or at least similar effects are obtained for both situations (in simulator and in real life) (Törnros 1998). According to Wang et al. (2010), when relative validity is defined as having the same order and direction of driver differences, one refers to an identical rank ordering of conditions. However, when relative validity additionally requires the same magnitude of effects to be established, one requires differences between conditions to take on the same numerical values. Thus, it is not necessary to obtain identical numerical values to establish relative validity, but it is crucial for the intervals between conditions to be equal (Klüver et al. 2016).

In our studies, fidelity of the driving simulator was the degree of realism the driving simulator provides the drivers. To increase the physical fidelity of the driving simulator, a curved screen with 180^0 wide view was placed in front of the driver. To increase the behavioural fidelity, an actual car was place in front of the screen. Relative validity of the driving simulator is already established by the previous studies which were conducted using the same simulator (Ariën et al. 2012, Hussain 2017). Based on the degree of realistic driving experience provided by the driving simulator, driving simulators can be divided into low, medium, and high fidelity driving simulators. These types are explained in the following section.

2.3.1 Low Fidelity Driving simulators

Low fidelity driving simulators have the simplest hardware configuration. They consist of a single or multiple desktop monitors or a head mounted display as an output device and simple gaming controllers as input device. Special controllers such as steering wheel and foot pedals (i.e. accelerator and brake pedals) can also be connected to the main computer. To increase the realism of the simulator, a gear changing device can also be connected for manual transmission. The processing power of the main computer does not always need to be very high. Simple speakers can be used to produce environmental sounds. An example of low fidelity driving simulator is shown in the Figure 2-2.

(a) (b)

Figure 2-2: Low fidelity driving simulators (a) with a single desktop display (Allen et al. 2007), (b) with multiple desktop displays at IMOB.

2.3.2 Medium Fidelity Driving Simulators

Medium fidelity driving simulators offer a more realistic driving experience compared to low fidelity driving simulators. They are called medium fidelity as their cost as well as the degree of realism falls in between low and high fidelity driving simulators. A medium fidelity driving simulator consists of a CPU, input devices can be steering wheel, foot pedals and gear box. Output devices include three monitors, which can provide a 135-degree field of view. A single driving seat from a car can be installed on a platform in front of the monitors. This platform can be fixed base or a moving hexapod system which allows movements across XYZ axis of the seat. The nature of output devices can increase the fidelity of the simulator and at the same time, its cost. Some types of medium fidelity driving simulators are shown in Figure 2-3. Some configurations of fixed driving simulators include a mock – up car in place of a driving seat. The field of view is also changed from 135 to 180 degrees. The reason that this kind of simulator configuration falls under medium fidelity category is the simulator does not produce motion effects because of it being fixed base. Figure 2.5 shows a simulator with this configuration.

(a) (b)

FIGURE 2-3: medium fidelity driving simulators (a) with fixed base (at IMOB, (b) with moving base (Mechanical simulation corporation 2018)

2.3.3 High Fidelity Driving Simulators

High fidelity driving simulators are the most expensive driving simulators. The processing computer in a high fidelity driving simulator is the most sophisticated one with very high processing power. In the high fidelity simulators, the driving seat in the medium fidelity simulator is replaced by an actual car. The virtual environment is presented on a broken or a seamless screen in front of the car by means of multiple projectors projecting a synchronized image.

The height of the car is adjusted such that the driver's eye position is similar as in reality. A 3D auditory feedback is also provided to produce sounds as realistic as possible. Vibrations may or may not be provided. Usually, a separate room or sometimes, a separate building is required to place the high fidelity driving simulator. The actual car can be placed on a hexapod system or in a dome depending upon the movements provided in xyz plane.

The most advanced driving simulators consist of a dome resting on a hexapod system to create motions around dome's axis. Inside the dome, multiple projectors produce a high-quality 360-degree image on seamless screens. Typically, an actual car is placed on a platform which rotates accordingly to provide realistic movements when the driver makes a left, right or a U-turn. Besides this, in the most advanced simulators, the entire dome assembly is also capable of moving in X and Y plane. This creates real acceleration and deceleration feelings. Examples of advanced driving simulators built across the world are National advanced driving simulator (NADS) in Iowa USA, Toyota's advanced simulator in Susanoo City in Japan, Mercedes Benz driving simulator in Stuttgart, Germany. These are shown in the Figure 2-4.

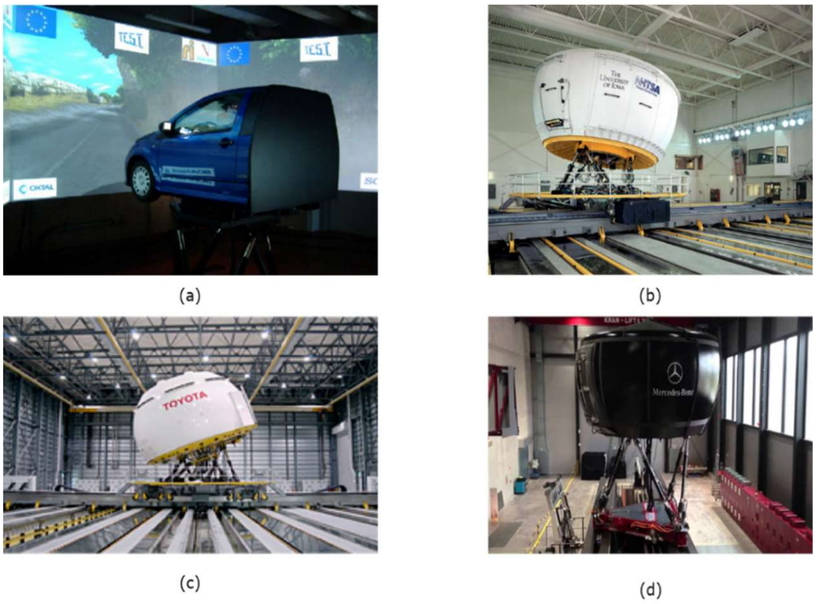


Figure 2-4: High fidelity driving simulators (a) Driving simulator with movements limited to its own axis (Galante et al. 2010), (b, c, and d) most advanced driving simulator at NADS University of Iowa (The University of Iowa 2014), Toyota japan(Toyota 2013), and Mercedes Benz (Klüver et al. 2016)respectively.

Advantages and disadvantages of driving simulators are directly linked with the types of the driving simulator. In general, a bird's eye view on advantages of driving simulators is provided in the following section.

2.4 Advantages

a. Driving simulators provide complete control over weather conditions (i.e. rain, sunny, snow, wind etc.), road conditions (i.e. lane width, surface friction, geometry of the road etc.), and behaviour and type of virtual traffic based on the research question (De Winter et al. 2012). These conditions can also be reproduced at will by the researcher in the driving simulator. Different participants at different locations can drive in exactly similar conditions. This is useful in creating standardized tests and reproducing the research results. For example, Bella and Calvi (2013) used driving simulators to investigate the effects of night time on human behaviour. Konstantopoulos et al. (2010) investigated driving behaviour under day, night and rainy weather conditions. Both of these studies used driving simulator as an experiment tool because of its characteristics of controllability and reproducibility of the situations.

b. Driving simulators enable researchers to study human responses resulting in dangerous situations without facing any physical damage which is very difficult to study in real life (De Winter et al. 2012). Human responses towards the situations such as collision and close encounters can be studied and measures can be suggested to modify the behaviour in such situations. According to Flach et al. (2008), driving simulators provide drivers an opportunity to learn from their mistakes in a forgiving environment. Various studies have been conducted in past which required drivers to encounter a dangerous situation which might result in property damage if conducted in real life. For example, experimental design in Gómez et al. (2011) study for investigation of advanced yield markings included a sudden appearance of a pedestrian on the road. Drivers vigilance was then analysed based on the stimulus. Various other studies have used driving simulator because their experimental methodology required exposure of the drivers to an unsafe situation (Bella 2005, Konstantopoulos et al. 2010, Underwood et al. 2011, Meuleners and Fraser 2015).

c. Driving simulators provide new opportunities for feedback about different road designs. Data for the road designs which have not been yet constructed in real world cannot be collected. Driving simulators can provide the data for such designs before they are built in the real world (Bella 2009, Jamson et al. 2010, Lee et al. 2011). In this way, driving simulators can contribute significantly in increasing safety of the road design.

d. Driving simulators provide a wide range of variables for which data can be collected. Parameters which describe driving behaviour such as longitudinal and lateral speed, acceleration/deceleration, lateral and longitudinal distance, brake count etc. are few examples of the variables. Data from eye tracker helps in investigating the eye movements of the drivers along with their facial expressions (anxiety).

e. Driving simulators are an efficient and economical research tool for conducting research (Lee et al. 2002, Bella 2009, Konstantopoulos et al. 2010, Klüver et al. 2016). Conducting field research requires lots of time and financial resources which are relatively lower for driving simulator studies.

2.5 Disadvantages

Besides their advantages, there are some disadvantages of the driving simulators as well. These disadvantages should be kept in mind while designing the research methodology and selecting the type of driving simulator. Some of the disadvantages of driving simulators are

a. Realism: While driving in a driving simulator, no matter whether it is a low fidelity or high fidelity simulator, a participant always knows that no matter what happens in the simulation (i.e. collisions with pedestrians or other vehicles), there will be no physical damage. This realization always makes behaviour in dangerous situations different than what will be in real life.

b. Not all details of a real world scenario can be created in the virtual scenario. No matter how detailed and close to real world a virtual scenario may be, there will always be few elements that makes it less realistic. Moreover, putting too much details in the scenario will have a negative impact on processing capacity of the computer.

c. External validity: Low fidelity simulators might result in unrealistic driving behaviour and produce invalid results. This is because simulator fidelity is known to affect the users opinion (De Winter et al. 2012). Increasing fidelity of the driving simulators also increases its cost. Hence, the type of driving simulator fidelity required should be in line with the research question.

d. Simulator Sickness: Driving simulations may cause discomfort to various persons in different ways. This discomfort sometimes may result in feeling sick. Due to simulator sickness, a participant might not be able to drive at all or might drive unnaturally. Avoiding long driving scenarios in the experiment and giving drivers short breaks during the experiment may help in reducing the effects of simulator sickness (De Winter et al. 2012). Increase in fidelity of the driving simulators might also increase the risk of simulator sickness (J.C.F de Winter et al. 2007, Mullen et al. 2010).

The advantages of the driving simulators allow us to investigate a wide range of problems e.g. road design, human behaviour etc. To minimize the effects of the disadvantages of the driving simulators, the methodology needs to be designed very carefully. Particular steps taken at the right moment can help in minimizing the disadvantages of driving simulators explained above. In all of our case studies, participants were given a brief explanation about the driving simulators and were asked to drive as they would in the real world. This helped in minimizing the negative effects of realism on our collected data.

Though it is true that not all of the world details can be created in the driving simulators, the most important environmental characteristics which drivers can notice can be created in the driving simulator program. However, again careful selection of such characteristics is important to make the driving simulator experience more realistic. In our case study about the perceptual road markings

(Chapter 5), the two curves selected from the real world were created as close to the real world as possible.

Nowadays, as discussed in previous sections, the problem of external validity can be overcome by increasing the fidelity of the driving simulators. Though it might increase the cost of the driving simulator, it also increases the scope of research questions that can be studied. In all our three case studies, medium fidelity driving simulator was used.

There are various ways to overcome simulator sickness during the experimentation in driving simulator studies. In our experiments, for example, we kept the room temperature between 20 to 25^{0}C. The room was kept properly ventilated so that the fresh air was available to the participants. The duration of scenarios were kept as minimum as possible and participants were allowed to take 2 to 5 minutes pause between the scenarios.

The selection of a driving simulator highly depends on the type the research question which needs to be addressed. In the next section, selecting a driving simulator is explained when the intended purposes of the driving simulator is to evaluate safety of the road design.

2.6 Selection of a Driving Simulator (Hardware)

For studying road design using a driving simulator, it is possible that not all types of road designs can be studied using the same type of simulator. Increasing fidelity of the driving simulator might not be a good option in every situation and it is possible that intentional deviation from reality produces valid results (Reed and Green 1999, Severson et al. 2007). Selecting a suitable driving simulator depends on the research question. For example, studying simple gap acceptance decisions (e.g. when turning left at an intersection), there is no need to use an advanced simulator and a low fidelity system might do perfectly (as long as the field of view is large enough to oversee the entire intersection that is relevant to make a left-turn decision). However, for studying the driving dynamics (e.g. lane position, acceleration/deceleration) in a curve, then a low fidelity system might not produce valid results as it cannot reproduce g-forces (no moving platform).

Similarly, for a simpler research question such as evaluating the placement and size of sign boards and its comprehensibility, using a high fidelity driving simulator might be inefficient since the same job can be done using a low fidelity simulator.

Lee et al. (2011) proposed which type of driving simulator will be effective in studying which types of road design research question and associated the characteristics of the driving simulator which might be important with those research questions. Table 2-1 presents the type of simulators that are suitable to study different types of road design scenarios according to Lee et al. (2011). From the table, it can be observed that the use of a high fidelity driving simulator is especially effective in studying the most complex road design questions. However, most of the road design aspects can also be studied effectively using a medium fidelity driving simulator. This does not mean that the use of high fidelity systems or the most advanced driving simulators cannot be justified. It only means that driving behaviour can be studied more accurately as we shift from low towards high fidelity simulators.

2.6.1 Driving Simulator at Hasselt University

The driving simulator at Hasselt University, Belgium is located at the Transportation Research Institute (IMOB). It is a medium fidelity fixed base driving simulator in which an actual car (Ford Mondeo) is placed in front of a curved seamless screen (diameter = 5m). Three overhead projectors project a total resolution of 4200 by 1050 pixels at a frame rate of 60 Hz. The same driving simulator was used in all three case studies included in this thesis.

Up till now, only hardware characteristics of driving simulators have been discussed. All these hardware devices, no matter how sophisticated they might be, are only useful if the driving environment is created as realistic as possible. The virtual environment is created in a virtual scenario creation program. How these virtual scenarios are programmed depends on the simulator software being used. However, the scenario creation process looks very similar for most software. A brief overview of a driving simulator scenario creation process is provided in the following section.

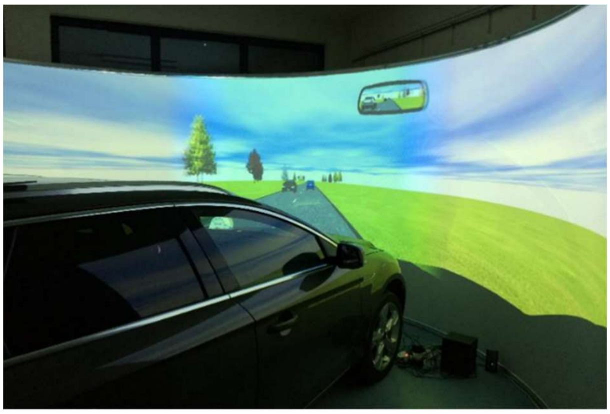


Figure 2-5: Driving Simulator At Hasselt University, IMOB.

2.7 Driving Simulator Scenario Creation Process

There are too many driving simulator software on the market to elaborate on the differences between each of them. The scenario creation process is different for all these programs. Based on the differences in scenario creation process, driving simulator programs can be divided in to two categories. These are graphical based design and scripting language. In graphical based design process, the virtual world containing the road environment is created in the simulator program. Some simulator programs require third party software to create the virtual environment. This virtual environment is then used in the simulator program for creation of driving simulation e.g. static and dynamic objects. Minisim is an example of a driving simulator program whose scenario creation process is graphical based. In language based programs, the virtual world is created by means of a scripting language. The static and dynamic objects are recalled in the language from the model library provided in the simulator program. Customized 3D models can also be included in the model library but these models require to be first created using third party software and then converting them to the file format compatible with the simulator program. Stisim Drive is an example of a language based program which uses a scripting language for creation of virtual environment. However, the basic information required in creation of scenarios is more or less the same for all programs. Santiago-Chaparro et al. (2011) proposed a general framework involving different steps of the scenario creation process for the purpose of a Road Safety Audit (Figure 2-6).

The first step in the scenario creation process for road design is to make sure that the road design is available. Usually, 2D drawings are obtained for the road designs. From these 2D drawings, a 3D model of the road design is created. There are various tools available to convert 2D drawings or models into 3D models. Some examples are 3D Studio Max, AutoCAD Civil 3D, Presagis Creator etc (The University of Iowa 2011).

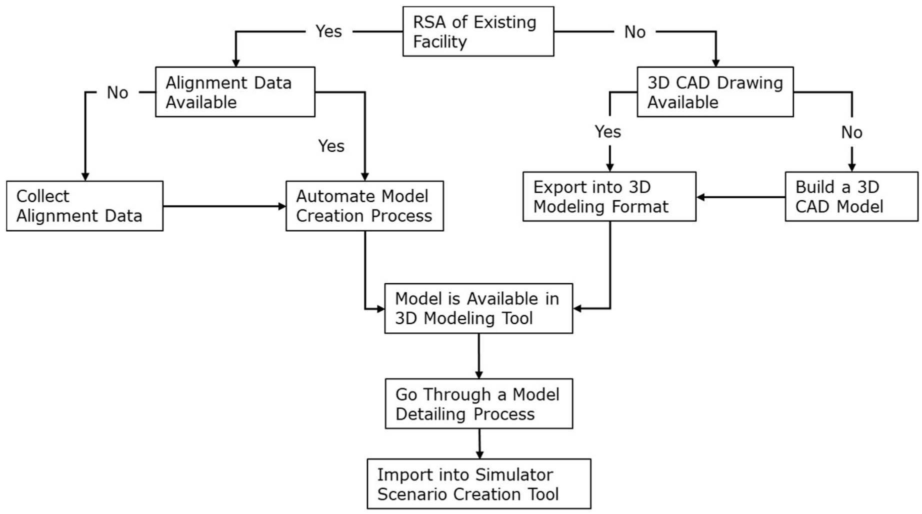


Figure 2-6: Scenario Creation Process (Santiago-Chaparro Et Al. 2011)

One of the most challenging tasks in scenario creation is to create 3D models as all elements of the virtual environment such as road geometry (e.g. horizontal and vertical alignments, gradients, super elevation etc.), bridges, road side objects (e.g. trees, buildings etc.), road signs etc., are included in the 3D model. This procedure is called geo-specific data base modelling and is defined as the process in which the real world driving environment is replicated in a virtual driving simulator environment as much as possible. This term should be differentiated from the research where the virtual road environment created in the simulator is imaginary (Yan et al. 2008). However, one of the limitations of a driving simulator is that not all elements of the real world can be inserted in the virtual environment.

This is because of the fact that virtual scenarios made with too many details become too heavy to be rendered by the simulator CPU hereby negatively impacting the frame rate of the simulation. Hence, a compromise has to be made on elements of the real world to be included in the virtual scenario.

There is no such criterion to determine which elements of the real world should be included in the virtual scenario. There is also no limit on the details with which these objects are designed. Objects with a high design precision contain much more polygons than objects designed with smaller precision and will also affect the rendering capacity of the system. Therefore, the selection of elements greatly depends on the expertise and skills of the person designing the scenario. However, keeping in mind the driver's field of view can help in the selection of elements. Without having an impact on the experience for the participant, objects that are not in the central field of view can be designed with smaller precision as the driver will not actively interact with these objects during driving. The lower design quality of such objects will therefore remain unnoticed to the participant. For example, if there are lots of trees placed at the road edge, a small structure placed behind the trees will not appear in driver's vision. Hence, including that structure in the scenario model is unnecessary and will be a burden on the computer processor.

Creating 3D models of road side objects like different types of trees, buildings etc., requires special skills. It is also a time consuming task as the level of details put into the models will require an increased processing ability of the computer. Hence, selection of the extent for level of detail depends on the type of road environment that needs to be created. For example, if a building will appear only for a very short interval of time in the driver's vision, there is no need to spend a long time putting a lot of graphical details into that object.

After a 3D model of the road design has been created, the next step is to insert traffic into the virtual environment. Some driving simulator programs require additional tools for inserting simulated traffic vehicles. For example in case of the MiniSim, an additional program ISAT is used to insert traffic (The University of Iowa 2011).

Table 2-1: Matching Simulator Characteristics And Simulator Types With Road Design Issues (Lee et al. 2011)

	Simulator Characteristics							**Simulator Type (Fidelity)**			
Design Issue	**Display**	**F.O.V**	**Cab realism**	**Control input**	**Auditory cues**	**Vehicle dynamics**	**M & V**	**Desktop**	**Low**	**Medium**	**High**
Road Signs	●	◒						PE[a]	PE[a]	E	IE[c]
Lane or path selection	◒	●	◒	●		●		PE[b]	PE[b]	E	E
Driver reactions to barriers, taper, etc.	●	○		●	○	●	○	PE	E	E	IE
Driver behaviour on work zone approaches	●	○		●	○	●	○	PE	E	E	IE
Driver behaviour at complex arterial intersections	●	●	◒	●	○	●	◒	NE	PE	E	E
Road Design features	◒	●	◒	●	○	●	◒	NE	PE[b]	E	E

NOTE: Blank = no importance; ○ = low in importance; ◒ = moderate importance; ● = high importance, PE= Possibly effective, E=effective, NE=not effective, IE=Inefficient

[a]Dependent on display resolution

[b]Dependent on field of view

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

Usually, driving simulator programs consider vehicles as individual events meaning that each individual vehicle has to be inserted exclusively. The behaviour of vehicles also has to be defined individually. This makes addition of traffic in the virtual environment a challenging task. Some driving simulator programs also support exchange of data with micro simulation programs such as VISSIM that allow them to insert vehicles based on traffic flow simulations (Ruyter 2016). Such micro simulation software include various traffic models (e.g. car following models) that define the behaviour of simulated vehicles. However, not all driving simulator programs do so hence, insertion of vehicles becomes one of the most important task as vehicles behaving unrealistically will not give a realistic driving experience. This also makes the role of the designer more important as the designer with good knowledge of traffic behaviour and drivers field of view will be able to create a realistic traffic stream.

2.7.1 Driving Simulator Program at Hasselt University

In this thesis "STISIM Drive version 3" is used to create scenarios. The scenario creation process is relatively easy in this program compared to other software. The reason is the different scenario creation process. A virtual driving scenario in STISIM is created using a scenario definition language (SDL), which is a scripting language developed for STISIM Drive to define different events in a scenario run.

Most of the 3D objects such as buildings, trees, pedestrians, etc., are included in the model library of the program. However, customized 3D models can also be inserted by converting them in the format supported by the simulator program. However, creation of those 3D objects is done using third party graphic software as explained in the previous section.

Each simulated traffic vehicle is considered as a separate event. This means that each simulated vehicle needs to be inserted individually and different criteria can be defined to trigger them. Simulated traffic vehicles in the traffic stream follow the path defined by the designer. The vehicles try their best to avoid collision with the driver's vehicle. Behaviour of each vehicle like changing lanes, making turns, turning on direction indicators etc. can be controlled individually.

2.8 Data Collection

One of the main advantages of driving simulators is that they offer data collection for a wide range of variables. Approximately 60 variables related to the driving behaviour can be collected. These variables include speed (longitudinal and lateral), acceleration (longitudinal and lateral), lateral position, braking counts, gear changes, turning indicators, number of crashes, steering wheel angle, time to collision (TTC), to name a few. Installation of additional devices such eye tracker, EEG, and heart rate monitor can increase the range of parameters for which data can be collected. Usually, an eye tracker is used to record eye movements of the drivers (sometimes also head movements and facial expressions). However, selection of such additional devices depends on the type of the research question. For example to study the risk perception of the drivers, eye tracker is used (Pradhan et al. 2005, Pollatsek et al. 2006, Palinko et al. 2010, Underwood et al. 2011). For studying the drowsiness of the drivers, driver alertness and mental fatigue, EEG can be used (Risser and Ware 1999, Åkerstedt et al. 2005, Yeo et al. 2009, Zhao et al. 2012). For monitoring mental workload, effects of alcohol, and stress levels of the drivers, heart rate monitors can be used (Fairclough and Graham 1999, Brookhuis and de Waard 2010, Sahayadhas et al. 2012). Nevertheless, some attributes of human cognition are non-tangible (e.g. level of comprehension, behavioural intentions, attitudes, temptations). For such variables, the use of questionnaires can be helpful. Usually, pre-questionnaire ask information such as age, gender, driving experience, their driving attitude. Questions regarding the driving simulation are asked in the post questionnaire. These questions ask the participant to provide information about the driving experience in the driving simulator. Other questions can also be asked depending upon the type of research question under study. The questionnaire data is beneficial in assessment of the subjective road safety of the design.

As STISIM Drive provides data for a wide range of variables, data for all variables is not always useful. Selection of variables for data collection depends on the research question. For example, for the studies included in this thesis in chapter 4 and chapter 5, longitudinal speed, longitudinal acceleration, and lateral distance were the variables for which data was obtained from the driving simulator.

Explanation for selecting these parameters is provided in the corresponding chapter.

The output file of the STISIM drive is in ".dat" format. This file is actually a log of all the events executed during a single run. Data for the required variables is extracted from the "dat" file using MATLAB, processed and stored in a MATLAB database. This database can then be used for data analysis.

According to the characteristics of the driving simulator hardware and the driving simulator program available at the Transportation Research Institute (IMOB), the scenarios were designed for all three research studies included in this thesis. Perspective of a car driver was one the key factors which defined the basis for creation of road environment and interaction of traffic vehicles with the driver vehicle. In following chapters, the three research studies conducted in this research are discussed in detail. Conclusions, future research and limitations are provided in the last chapter of this thesis.

2.9 References

Åkerstedt, T., et al. (2005). "Impaired alertness and performance driving home from the night shift: a driving simulator study." Journal of sleep research **14**(1): 17-20.

Allen, R. W., et al. (2007). "The effect of driving simulator fidelity on training effectiveness." DSC 2007 North America.

Ariën, C., et al. (2012). "The effect of pavement markings on driving behavior in curves: A driving simulator study." Transportation Research **13**: 14.

Bella, F. (2005). "Validation of a driving simulator for work zone design." Transportation Research Record: Journal of the Transportation Research Board(1937): 136-144.

Bella, F. (2009). "Can Driving Simulators Contribute to Solving Critical Issues in Geometric Design?" Transportation Research Record: Journal of the Transportation Research Board **2138**: 120-126.

Bella, F. and A. Calvi (2013). "Effects of simulated day and night driving on the speed differential in tangent–curve transition: a pilot study using driving simulator." Traffic injury prevention **14**(4): 413-423.

Brookhuis, K. A. and D. de Waard (2010). "Monitoring drivers’ mental workload in driving simulators using physiological measures." Accident Analysis & Prevention **42**(3): 898-903.

De Winter, J., et al. (2012). Advantages and disadvantages of driving simulators: A discussion. Proceedings of Measuring Behavior, Citeseer.

Fairclough, S. H. and R. Graham (1999). "Impairment of driving performance caused by sleep deprivation or alcohol: a comparative study." Human factors **41**(1): 118-128.

Fisher, D. L., et al. (2011). Handbook Of Driving Simulation for Engineering, Medicine, and Psychology. USA, CRC Press.

Flach, J. M., et al. (2008). "Playing twenty questions with nature (the surprise version): reflections on the dynamics of experience." Theoretical Issues in Ergonomics Science **9**(2): 125-154.

Galante, F., et al. (2010). "Traffic calming along rural highways crossing small urban communities: Driving simulator experiment." Accident Analysis & Prevention **42**(6): 1585-1594.

Godley, S. T., et al. (2002). "Driving simulator validation for speed research." Accident Analysis & Prevention **34**(5): 589-600.

Gómez, R., et al. (2011). "Do advance yield markings increase safe driver behaviors at unsignalized, marked midblock crosswalks? Driving simulator study." Transportation Research Record: Journal of the Transportation Research Board(2264): 27-33.

Hussain, Q. (2017). The impact of perceptual countermeasures on driving behaviour in rural-urban transition road segments: A driving simulator study, UHasselt.

J.C.F de Winter, et al. (2007). Driving simulator fidelity and training effectiveness. Proceedings of the 26th European Annual Conference on Human Decision Making and Manual Control, Lyngby, Denmark.

Jamson, S., et al. (2010). "Driving simulators for robust comparisons: A case study evaluating road safety engineering treatments." Accident Analysis & Prevention **42**(3): 961-971.

Keith, K., et al. (2005). Roadway human factors and behavioral safety in Europe.

Klüver, M., et al. (2016). "The behavioral validity of dual-task driving performance in fixed and moving base driving simulators." Transportation Research Part F: Traffic Psychology and Behaviour **37**: 78-96.

Konstantopoulos, P., et al. (2010). "Driver's visual attention as a function of driving experience and visibility. Using a driving simulator to explore drivers' eye movements in day, night and rain driving." Accident Analysis & Prevention **42**(3): 827-834.

Lee, J., et al. (2011). "Matching simulator characteristics to highway design problems." Transportation Research Record: Journal of the Transportation Research Board(2248): 53-60.

Lee, J. D., et al. (2002). "Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator." Human factors **44**(2): 314-334.

Mechanical Simulation Corporation (2018). "Driving simulator." from https://www.carsim.com/products/ds/index.php.

Meuleners, L. and M. Fraser (2015). "A validation study of driving errors using a driving simulator." Transportation Research Part F: Traffic Psychology and Behaviour **29**: 14-21.

Mullen, N. W., et al. (2010). "Driving performance and susceptibility to simulator sickness: Are they related?" American Journal of Occupational Therapy **64**(2): 288-295.

Palinko, O., et al. (2010). Estimating cognitive load using remote eye tracking in a driving simulator. Proceedings of the 2010 symposium on eye-tracking research & applications, ACM.

Pollatsek, A., et al. (2006). "Using eye movements to evaluate a PC-based risk awareness and perception training program on a driving simulator." Human factors **48**(3): 447-464.

Pradhan, A. K., et al. (2005). "Using eye movements to evaluate effects of driver age on risk perception in a driving simulator." Human factors **47**(4): 840-852.

Reed, M. P. and P. A. Green (1999). "Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task." Ergonomics **42**(8): 1015-1037.

Risser, M. R. and J. C. Ware (1999). Driving simulation with EEG monitoring in normals and obstructive sleep apnea patients. Annual Proceedings/Association for the Advancement of Automotive Medicine, Association for the Advancement of Automotive Medicine.

Roza, Z. C. (2004). Simulation fidelity theory and practice: a unified approach to defining, specifying and measuring the realism of simulations, DUP Science.

Ruyter, M. d. (2016). The road safety of merging tapers: Measuring the effect of varying geometric designs and traffic conditions on driving behaviour at merging tapers. Civil Engineering. Delft, TU Delft. **Masters**.

Sahayadhas, A., et al. (2012). "Detecting driver drowsiness based on sensors: a review." Sensors **12**(12): 16937-16953.

Santiago-Chaparro, K., et al. (2011). Virtual Road Safety Audits Using Driving Simulators: A Framework. 3rd International Conference on Road Safety and Simulation.

Severson, J., et al. (2007). Driving Simulation: How Low Can You Go? Driving Simulation Conference.

The University of Iowa (2011). ISAT User's Guide: National Advanced Driving Simulator.

The University of Iowa (2011). TMT User Guide: National Advanced Driving Simulator.

The University of Iowa (2014). "NADS-1." from https://www.nads-sc.uiowa.edu/sim_nads1.php.

Törnros, J. (1998). "Driving behaviour in a real and a simulated road tunnel—a validation study." Accident Analysis & Prevention **30**(4): 497-503.

Toyota (2013). "Pursuit for Vehicle Safety: Driving Simulator."

Underwood, G., et al. (2011). "Driving simulator validation with hazard perception." Transportation Research Part F: Traffic Psychology and Behaviour **14**(6): 435-446.

Wang, Y., et al. (2010). "The validity of driving simulation for assessing differences between in-vehicle informational interfaces: A comparison with field testing." Ergonomics **53**(3): 404-420.

Yan, X., et al. (2008). "Validating a driving simulator using surrogate safety measures." Accident Analysis & Prevention **40**(1): 274-288.

Yeo, M. V., et al. (2009). "Can SVM be used for automatic EEG detection of drowsiness during car driving?" Safety science **47**(1): 115-124.

Zhao, C., et al. (2012). "Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator." Accident Analysis & Prevention **45**: 83-90.

3 Drivers' Crossing Behaviour Between Express And Local Lanes With Soft Separation: A Driving Simulator Study

This study has been published as the following paper:

Awan H.H., Sajid S.R., Declercq K., Adnan M., Pirdavani A., Alhajyaseen W., and Brijs T. (2018). Drivers' crossing behaviour between express and local lanes with soft separation: a driving simulator study. In: Advances in Transportation Studies: an international journal, Special Issue, Vol 1.

3.1 Abstract

In different countries, hard separation is adopted as a technique to separate express and local lanes. However, in case of an incident, especially on the express lane, traffic jams can occur as there is no escape route. Emergency services are then required instantly to remove the obstruction. In some cases, even traffic diversion needs to be organized leading to time loss and which may possibly also affect the traffic in adjacent lanes. In this study, an alternative flexible geometric design approach called 'soft separation' is evaluated having less side-effects in case of such calamities. A virtual environment using a driving simulator is used to evaluate 4 different types of soft separations. More specifically, driver behavior and driver temptations to cross different types of soft separations on the express lane are studied. These include: (1) a solid double line (2) cross hatch marking (3) tubular delineators and (4) vegetation / grass strip. Moreover, for each of the soft separation types, drivers were exposed to two different traffic conditions. In the first traffic condition, other vehicles in front did not cross the separation from express to local lanes whereas in the second condition, they did so. Results indicate that tubular delineators and the vegetation strip are more effective in restricting drivers to cross the separation. Implications for road design practice are given.

Keywords: Crossing behaviour, Driving simulator, Express and local lanes, Generalized Estimating Equation, Soft separation

3.2 Introduction

Managed lanes are widely used in order to increase the capacity of existing freeways without spending considerable amounts of resources on construction (Fuhs and Obenberger 2002). Therefore, freeway traffic is physically separated into two different pathways to maintain appropriate flow of traffic by utilizing the road capacity to its maximum. This study addresses the separation between express and local lanes, in which lanes are divided according to their destinations. The main objective of this separation is to limit the impact of local traffic (e.g. traffic having its origin or destination in a city) on the operational performance of express lanes (i.e. carrying long distance traffic) and vice versa. This improves the level of service along express lanes by restricting the disturbances caused by weaving manoeuvres between long distance and local traffic, hereby leading to fewer crashes and shorter travel times.

Express lanes can be separated from local lanes using different road design methods. These methods include hard separation (e.g. concrete barriers, median, etc.) and soft separation (e.g. pavement markings, tubular delineator etc.). Each of the above methods has their own pros and cons. For instance, safety and durability is the highest for hard separation and the lowest for pavement markings. Recently, several countries in Europe (such as The Netherlands) have separated express and local lanes using hard separation (van Loon 2015) to separate long distance traffic from local traffic around big cities. However, because of the durable and non-removable nature of hard separation, long traffic jams can occur when traffic is blocked, especially in express lanes as there is no free 'escape route' (Davis 2011). Remedial measures for interrupted traffic flow on express lanes might require removal of barriers and hence, result in increased maintenance cost and travel time, which results in the failure of express lanes to serve their intended purpose. Road authorities are, therefore, looking for different methods of road separation that are flexible to allow traffic to crossover into adjacent lanes under interrupted traffic conditions while at the same time ensuring safety and capacity under normal conditions. To the best of our knowledge, no studies have previously investigated separation crossing behaviour under different types of soft separation. In this research, four different separations are evaluated; 1) a solid double line (SDL) 2) cross hatch marking (CHM) 3) tubular delineators (TD) and 4) vegetation or grass strip (VS). Usually, VS is used to separate two different classes of roads (e.g. main road and service road) or to separate different flow directions of the high speed roads (e.g. median). The use of VS is considered as a soft separation technique in this study as the height of vegetation is considerably low such that it can be crossed, when needed.

To evaluate and compare different methods of lane separation, conducting an empirical study would be expensive and time consuming. Hence, a driving simulator is used in this study as it is a safe, efficient, and economical approach. A four lane freeway consisting of two express and two local lanes was created in the driving simulator. Scenarios included four types of separations as explained above. A crash situation with traffic jam in the express lanes downstream of the driver position was created on purpose to create a situation resulting in a partial closure of the express lane. Under these circumstances, the drivers' response to the traffic jam in the express lane was studied. Driver's temptations to cross the separation during the traffic jam were also collected by means of a follow-up questionnaire. Along with these four separation types, two different traffic conditions were also applied which may provoke drivers to cross the separation: the absence of traffic on the adjacent local lane and the presence of other vehicles in front crossing the soft separation.

This chapterr is further organized as follows: in the next section we carry out a literature review covering different aspects of this study such as managed lanes, separation types and driving simulator research. Then, the research methodology adopted is explained followed by the results and a discussion section. Finally, conclusions and practical road design recommendations are drawn and future research directions are discussed.

3.3 Literature Review

3.3.1 Managed lanes

Managed lanes are mostly classified as High Occupancy Vehicle (HOV) lanes and High Occupancy Toll (HOT) lanes. The lanes adjacent to managed lanes are described as General Purpose (GP) lanes. However, in some countries, managed lanes and general purpose lanes are named express and local lanes and traffic is separated on the basis of their destination (van Loon 2015). Especially around big cities, express lanes serve the purpose to carry uninterrupted long-distance traffic, whereas the local lanes serve the purpose to carry traffic that has its origin or destination inside the city. This way, weaving manoeuvres leading to traffic flow disturbance are avoided as much as possible. Hence, implementation of managed lanes can efficiently optimize the available freeway capacity. In order to understand the operational interaction between managed and general purpose lanes, Cooner and Ranft (2006) carried out a safety evaluation for concurrent flow of buffer-separated interim HOV lanes, retrofitted into two existing freeways in

Dallas. They observed an increase in crash rate between the HOV lane and the first adjacent general purpose lane. The crash rate was mainly related to the speed differential between these two lanes. Liu et al. (2011) examined the interaction between these lanes as a function of different separation types, number of managed lanes and operation strategies. According to their study, traffic in managed lanes is adversely affected by the congestion in general purpose lanes. Results indicated that application of tolls played an important role for separating and managing traffic on a HOT facility while a HOV facility was more affected by the separation type. Brewer (2014) analysed the safety of access points to a managed lanes facility built on Katy Freeway, Houston, Texas. He found that the design was safe and could accommodate even large volumes of traffic. All of the above studies used real field data to observe these behaviours. Cassidy et al. (2015a) and Cassidy et al. (2015b) observed that the traffic in managed lanes is adversely affected due to the frictional effect between managed and general purpose lanes. The intensity of frictional effect was found to be the highest during rush hours. They also found that the intensity of the frictional effect was the highest when traffic was separated using a solid white line and minimum when using concrete barriers. The use of soft barriers had an intermediate effect on the intensity of this frictional effect. Additionally, they found that the access points were prone to become bottlenecks. In continuation of a previous study, they used field data and simulation to analyse the operational behaviour of managed and general purpose lanes. They recommended that increasing the length of access to managed lanes from the current value of 400 m to 700 m can have better impact on the traffic but it should be increased according to the circumstances. They also concluded that limiting the times of day for carpooling will degrade travel conditions. Fitzpatrick et al. (2008) contributed in the development of guidelines for intermediate access to and from managed lanes. After examination of operations of five intermediate access sites, they recommended the length of the intermediate access to be between 396 and 610 m, and the width of the buffer to be minimum 1.2 m. Aforementioned studies mainly focused on the operational characteristics under different circumstances. To the best of our knowledge, a dangerous move such as crossing of the separation due to congestion on express lanes has not been yet studied.

3.3.2 Lane separation

There are several methods for separating express lanes from local lanes. These methods include hard barriers which are mostly made of concrete, and soft barriers which are mostly made of plastic or pylon, and pavement markings (Davis 2011). Hard separation, is considered to be the safest as it minimizes the frictional effect between express lanes and local lanes. But, in some special circumstances the drawbacks of hard separation become more prominent, for example in case of an accident on an express lane. Indeed, if the point of interference in the traffic flow is in between the access points, then this can result in the formation of long queues. In order to remove the obstruction, special equipment is required which can cause interruption in the traffic flow of adjacent local lanes. The use of soft separation and pavement markings can reduce these problems, but may also have a negative impact on safety by increasing the frictional effect or illegal lane crossings. According to Davis (2011), each separation can serve efficiently if used in the right circumstances. Hence, road sections where it is important to address the issue of traffic jams, soft separation can be a feasible option. When soft separations (e.g. tubular delineators) are used, Davis (2011) concludes that spacing between tubular delineators should be maximum 20 ft. (6 m). Cooner and Ranft (2006) proposed the width of a freeway barrier separation to be at least 18 ft. (5.5m) when soft separation or road marking is used. Kuchangi et al. (2013) describes effective uses of pylons (tubular delineators) in detail. In this study, a vegetation strip (VS) is also considered as a method of soft separation (VS). The motivation for the use of VS comes from the AASHTO Green book in which cross sectional designs for freeways at ground level are given (AASHTO 2011). VS are used to improve the aesthetics of roadways. It is hypothesized in this study that VS can also restrict drivers to cross the separation. In order to use VS as a soft separation, VS needs to be designed so that crossing through it is not impractical i.e. it can be crossed at very low speeds without causing damage to the vehicle. Due to the limitations of the driving simulator used in this study, the height of VS could not be considered. It is possible in real life that the VS have some height from the road level.

3.3.3 Driving simulation

Driving simulators have been used successfully in several previous studies to evaluate road geometric design or road marking and signage aspects. Bella (2008) investigated driving performance while approaching and departing a horizontal curve on a 2-lane rural road using a driving simulator. Benedetto and Benedetto (2002) conducted a study to validate the driving simulator for road geometry. The study demonstrated that a geometric design cannot be considered as safe without consideration of the human factor. Gómez et al. (2011) compared standard yield markings to advanced yield markings on crosswalks. The aim of the study was to observe drivers' response at crosswalks with different markings in case of a sudden appearance of a pedestrian. Bella and Calvi (2013) evaluated the safety of tangent-curve transitions during night time and day time driving using a driving simulator. In a study by Elefteriadou and Kondyli (2009) drivers' behaviour was studied while merging into a freeway using a focus group. Different diagrams/photos of various merging situations were presented to different participants of the focus groups and then results were analysed. However, the use of driving simulator may provide a more realistic behaviour from the focus group participants, as the participants will react to their experience while driving in such circumstances. It was also one of the recommendations of the study. Driving simulator, therefore, can also be used just as a presentation tool of the complex design features of the road environment. This allows participants to respond more appropriately in the post-questionnaire phase of the study regarding a particular scenario which they have already visualized and experienced. Concluding, driving simulators have demonstrated added value for studying interactive driver behaviour under different simulated road geometric design and traffic conditions.

3.4 Methodology

The driving simulator at Hasselt University, Transportation Research Institute (IMOB) consists of a static car mock up (Ford Mondeo) with a seamless, curved screen placed in front of the vehicle to create a 180 degree field of view for the driver. Interior functions of the car (i.e. radio, air-conditioning etc.) except direction indicators are idle. A force-feedback steering wheel, pedals and gear shift lever are connected to the simulator software for interaction with the scenario and data collection. Environmental sounds (i.e. sounds of simulator vehicle and surrounding traffic) were also produced. Data for the driving simulator was collected at a frame rate of 40-60Hz. Various road design and road marking studies (Arien et al. 2013, Ariën et al. 2014) have been conducted previously on the same driving simulator and its validity has been verified (Ariën et al. 2017).

Four virtual environments with a four lane, 5500 meters long motorway were created in STISIM Drive © version 3 with four different types of separations i.e. SDL, CHM, TD and VS separating the two express and two local lanes. In designing the SDL, two solid lines 0.3 m wide and 0.2 m apart were used as means of separating express lanes from local lanes as shown in Figure 3-1-a. AASHTO's Policy on Geometric Design of Highway and Streets (2011) was followed in determining different parameters such as lane marking's length and width etc.(FHWA 2010).

CHMs were made with 1.2 m wide and 0.2 m wide diagonal markings at 450 with 2.3 m distance between them (Figure 3-1-b). This specification was obtained from Traffic Signs Manual from the Transportation Department of London (Transport 2003). The height of TDs was considered one meter from the road surface and they were placed right in the middle of the area between the two 0.3 m wide solid lines 1.2 m apart. Centre to centre distance between the two adjacent TDs was kept 3 m (Fig. 3-1-c). These dimensions are based on the actual experiences obtained from application of TDs in real life (Davis 2011). For VS, the width of the

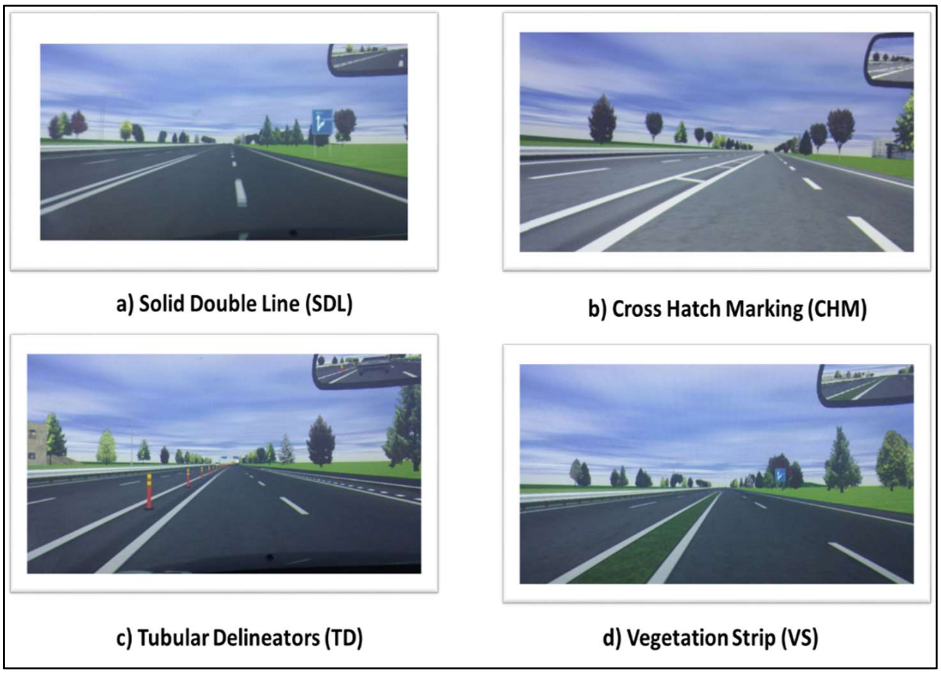


Figure 3-1: Driver's View Of Different Separation Types In Driving Simulator

separation was kept similar to the width of CHM and TD along with 0.3 m wide solid lines as shown in Figure 3-1-d. due to the absence of kinematic feedback in the driving simulator (vibration of the steering wheel, car seat etc.), the effect of the vertical height of the vegetation strip could not be investigated. Other objects such as buildings, trees etc. were also placed in the virtual environment for resemblance to the real world.

The motorway length designed for the scenario is presented in figure 3-2. The roadway is composed of four lanes, each 3.5 meters wide, with internal and external shoulders of 1 and 1.8 meters wide respectively. Lane separation markings were 0.15 meters wide, 3 meters long and 6 meters apart as per (FHWA 2010). The road started with a 300 meter long service lane with an arrow marking placed at 200 meters indicating the driver to merge into the motorway. The motorway after the initial merging is presented in figure 3-2.

At 300 meters, drivers were informed about the destination and upcoming access for express lanes through a cantilever gantry sign board. Before the opening to the express lanes, a double overhead sign was place with information about the

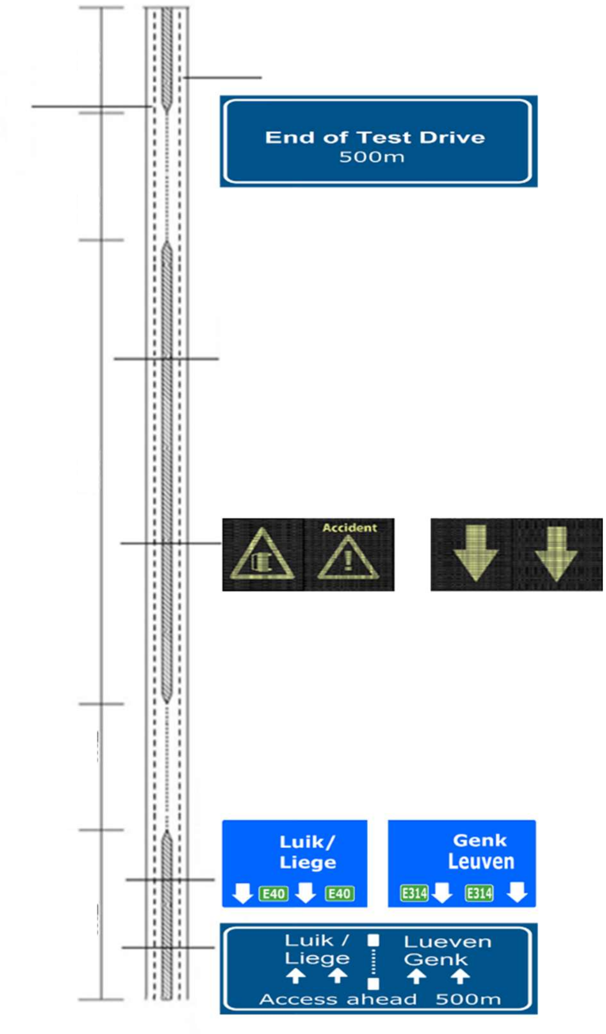


Figure 3-2: Scenario Plan

destinations and roads. Access of 600 meters was provided to the express lanes after the first 800 meters of the roadway as per (Cassidy et al. 2015a). After 2700 meters, a double overhead variable message sign (VMS) board was placed. This board warned the drivers about the occurred accident in the right express lane whereas a warning sign with the word "Accident" was displayed on the left express lane along with the information that there is no obstruction to traffic flow in local lanes. Just before 3700 meters, cars were waiting in the queue for traffic to resume as due to an artificial accident. Another 600 meters long opening to the express lanes was provided after 4100 meters, followed by a sign board displaying the message '*end of the scenario after 500 meters'* so that the drivers get mentally prepared and the completion of the scenario does not surprise them.

In reality, traffic jams/congestion may consume considerable duration of time resulting in increased travelled time. Those realistic timings were however impractical to reproduce in the driving simulator (i.e. it will take one person hours to complete the experiment). Hence, traffic jam durations were kept up to 120 seconds. Traffic on the local lanes was nearly absent (very few cars). Along with this, two traffic conditions were also created in the scenario so that participants may get tempted to cross the separation in this two minutes period of congestion. Details of these two conditions are explained below:

- Condition A: none of the vehicles from the queue cross the soft separation.
- Condition B: the driver could see 2 vehicles from the traffic jam queue crossing the soft separation and continue their journey on the local lanes.

Hence, eight test scenarios were created with four soft separation methods (SD, CHM, TD, VS) and two traffic conditions (crossing vehicles or not). All eight test scenarios were presented to each of the participants (within-subject design) in a counter-balanced way. In each scenario, participants started from the service lane and weaved into local lanes. The destinations on the sign board in the scenario were designed in such a way that in order to follow the destination briefed to the participants before the start of the experimental drive, they had to travel in the express lanes. When they weaved into the express lanes, they were informed through a VMS board about the closure of both express lanes due to an accident after almost 1000 meters. 1000 meters further, a queue of vehicles emerged due to the accident. In condition A, the traffic was partially resumed on the express lanes after 120 seconds and none of the vehicles from the queue crossed the separation. Partial resumption of the traffic means only the right express lane became open to the traffic while the other was still blocked due to the incident.

In condition B, after 100 seconds, one car from the queue started to cross the separation and resumed its journey on local lanes. After ten seconds, another car from the queue crossed the separation and followed the former car. Ten seconds later, the traffic was resumed in a similar pattern to the one in condition A.
In total, 49 participants volunteered for the driving simulator experiment. Data from five participants were not included in the statistical analysis as three of them suffered from simulator sickness and two showed extreme speeding behaviour. Out of the remaining 44 participants, 53% were male. The age range of the participants was 20-49 with an average age of 27.65. All drivers had a valid driver license and were regular drivers. Participants were students and staff members of Hasselt University and were invited via an email invitation.

The experiment was conducted in four steps. In the first step, participants received a brief introduction about the driving simulator and the test scenarios without revealing the purpose of the study. Participants were told to follow the instructions about the destination as provided via sign boards during the test scenario. Participants were also asked to fill out the pre-questionnaire and sign a consent form during this step. In the pre-questionnaire, questions about general information such as gender, age, education and driving experience were asked. In the second step, the participants were given a test drive on the driving simulator so that they could familiarize themselves with the simulator setup and the virtual environment. If needed, the participant could take another test drive until he/she felt sufficiently adapted to the simulator setup. In the third step, each participant drove all eight scenarios, and for each participant the order of the scenarios was randomized. The duration of each scenario was approximately five minutes. In the last step, participants were asked to fill out a post-questionnaire. Participants were asked to give feedback on their simulated driving experience and to also rate their temptation to cross the soft separation in each of the eight presented conditions as high, average, low or none. Participants who, during any of their simulator drives, crossed the separation in a particular scenario instead of waiting in the queue for traffic to resume were considered as highly tempted for that scenario.

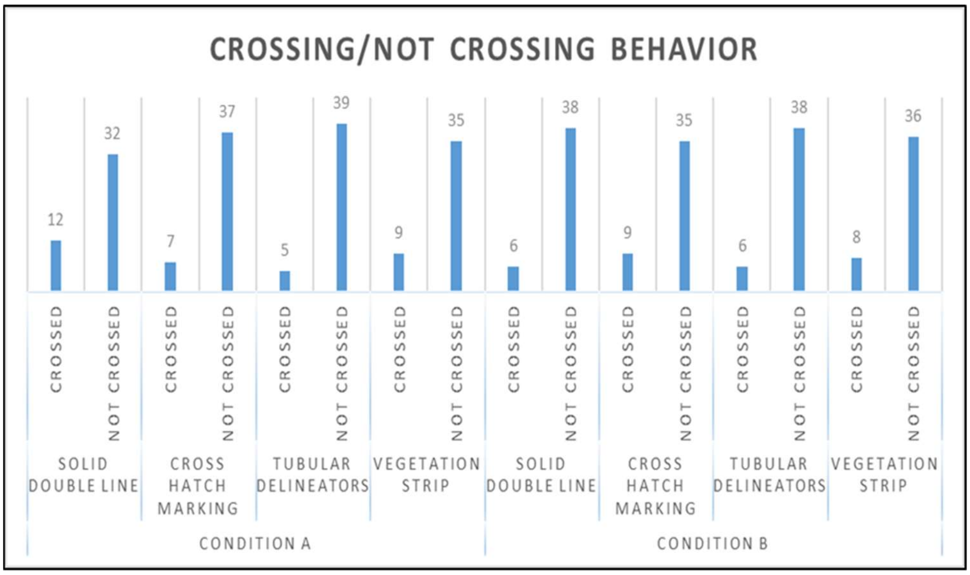


Figure 3-3: Composition of Crossing and Not Crossing Counts for Condition A and B

3.5 Results

In order to investigate drivers' attitudes towards the separation type and changes in their attitude due to the two traffic conditions described in the previous section, two variables were examined. These are actual *crossing behaviour* and their reported *temptations to cross the separation*. Data for the number of crossings is presented in figure 3.3 which was obtained from the lateral position of the driver on the road in the driving simulator and personal observation by the experimenter. Out of 44 participants, 12, 7, 5 and 9 participants crossed the SDL, CHM, TD and VS respectively in traffic condition A. Whereas, 6, 9, 6 and 8 participants crossed the SDL, CHM, TD and VS respectively in traffic condition B.

Further analysis of the crossing behaviour is carried out using an estimation of the generalized estimation equation (GEE) model with a logit link function. As the same participant is measured repeatedly over time, to account for the correlation, the GEE technique is preferred (Zorn 2001, Ballinger 2004, Hardin 2005). For the binary response variable (crossing = yes or no), it is assumed that if y_{ij} represents the outcome of individual i in condition j, for $i = 1, ..N$ and $j = 1, .. T$, and Pr $(Y_{ij}=1) = \mu_{ij}$, then the model formulation is given by

$$\log\left(\frac{\mu_{ij}}{1-\mu_{ij}}\right) = \boldsymbol{\beta}_o + \boldsymbol{\beta}_1 \boldsymbol{X}_{ij1} + \cdots + \boldsymbol{\beta}_p \boldsymbol{X}_{ijp} \qquad \text{Equation 3-1}$$

where, X_{ij1}, …, X_{ijp}, are the explanatory variables for individual *i* at time *j* and β_o, β_1, …, β_p, are the intercept and coefficient estimates. The SAS® GENMOD procedure was used to estimate the model and results are presented in Table 1 (*see Model A*). Among the explanatory variables, separation type (SDL, CHM, TD and VS), traffic conditions (A, B), and interactions between separation type, traffic condition and gender are considered, with separation type VS, traffic condition B and male as the reference categories. From Model A results in Table 3-1, it appears that none of the variables i.e. type of separation, traffic conditions, gender and interaction between separation type and traffic conditions have a significant effect on crossing behaviour of the participants. Several other combination of explanatory variables were also investigated such as age, driving license and education status. However, the results are not significantly different than the one reported in Table 3-1 in terms of model fitness.

Table 3-1: GEE Logistic Model Estimates

	Model A		Model B		Model C	
	GEE Model Estimates (Crossing Behaviour) based on equation (1)		**Cumulative Logit GEE Model Estimate (for Temptation Intensity) based on equation (2)**		**GEE Model Estimates (Temptation Intensity as Binary response) based on equation (1)**	
Parameter	***Estimate***	***Pr > |Z|***	***Estimate***	***Pr > |Z|***	***Estimate***	***Pr > |Z|***
Intercept_High	---	---	-0.1504	0.4537	---	---
Intercept_Average	---	---	0.5657	0.0039	---	---
Intercept_Low	---	---	1.2349	<.0001	---	---
Intercept	-1.5342	0.0007	---	---	-0.8170	0.0002
Separation _SDL	-0.3418	0.3142	0.7218	0.0072	-1.0210	0.0090
Separation_CHM	0.1460	0.7052	0.7780	0.0073	-1.1318	0.0025
Separation_TD	-0.3418	0.4130	-0.4508	0.1047	0.5521	0.0892
Stimulant_A	0.1460	0.7052	0.2049	0.4427	-0.5036	0.1624
Separation_SDL*Stimulant_A	0.7192	0.1020	-0.2308	0.5094	0.7161	0.0834
Separation_CHM*Stimulant_A	-0.4529	0.3135	-0.0795	0.8323	0.5036	0.2358
Separation_TD*Stimulant_A	-0.3543	0.4753	-0.4683	0.1688	0.7589	0.1372
Gender_Female	0.0655	0.9132	-0.5796	0.2238	0.5582	0.2624

It is however not necessarily the case that if a participant did not actually cross the soft separation during the simulation, that he or she could not have felt a certain temptation to do so. Therefore, all the participants were also asked to rate their temptations as high, average, low or none against all four separation types and the two traffic conditions. For those who actually crossed the soft separation, their temptation for a certain separation type was marked as. Table 3-2 presents the number of participants with high, average, low and no temptations for each of the presented experimental conditions.

Table 3-2: Composition of Temptation Intensities of Participants for all Separation Types Against Traffic conditions

	Traffic Condition A				**Traffic Condition B**			
Type	High	Average	Low	None	High	Average	Low	None
SDL	22	4	4	14	18	11	5	10
CHM	20	9	6	9	19	10	4	11
TD	6	5	9	24	11	2	8	23
VS	12	11	6	15	11	7	10	16

The similar technique as illustrated above is used for further analysis of participant temptations to different cross separation types under different traffic conditions. As the response variable in this case is ordinal and has multiple values (such as high, average, low and no temptation), instead of the logit link function, the cumulative logit link function was used to estimate the GEE model. If it is assumed that y_{ij} represents the response from individual *i* at time *j* that can fall in *k* = 1, …K. The cumulative probability can be defined as Pr ($Y_{ij} \leq k$) = $\mu_{ij}^{1} + \cdots + \mu_{ij}^{k}$. The formulation can be written as

$$\log\left(\frac{\Pr(Y_{ij} \leq k)}{1 - \Pr(Y_{ij} \leq k)}\right) = \beta_k + \beta_1 X_{ij1} + \cdots + \beta_p X_{ijp} \qquad k = 1, \ldots, K-1 \qquad \text{Equation 3-2}$$

where, all other parameters have their usual meanings. However, in this case K-1 intercept terms will be estimated corresponding to high, average and low temptation intensities. For measuring the probability of being *not tempted* the K-1th cumulative probability needs to be subtracted from 1. The model was estimated using the SAS® GENMOD procedure. The same explanatory variables were used as in Table 3-1 (*see Model B* results in Table 3-1).

The results for Model B in Table 3-1 show that there is no significant effect of the explanatory variables except for the separation type as it is the only variable which has a significant difference on the temptations. It is interesting to note that the intercept value is increasing with respect to decreasing intensity for temptation and that we also observe a negative coefficient for separation TD. This suggests that participants had a lower probability to have a higher temptation to cross for TD compared to SDL and CHM. Along with the model estimation results, the GENMOD procedure can also provide an output that mentions predicted probabilities for temptation intensity for each separation type. This output is shown in Table 3-2 for Model B whereas the probabilities presented in the Table 3-3 are cumulative probabilities.
The interpretation of the cumulative probabilities is as follows: in order to get the probability value for each particular level of temptation, the probability for the next level should be deducted. For example, the probability of high temptation for SDL in Table 3-3 is 0.4092. Now, the probability of average temptation for SDL is obtained by deducting the next value (which is 0.5864) from the previous, which results in 0.1772. Similarly, the probability of low temptation and no temptation for SDL is 0.1482 and 0.2654 respectively. The following observations can be deduced from Table 3-3:

- When the soft separation method is CHM, there is a 44.14% chance of high temptation, 17.65% chance of average temptation, 14.16% chance of low temptation and 25.05% chance of no temptation at all.
- For TD, there is a 16% chance of high temptation, 12.04% chance of average temptation, 15.17% chance of low temptation and 56.79% chance of no temptation at all.
- For VS, there is a 27.42% chance of high temptation, 16.18% chance of average temptation, 16.55% chance of low temptation and 39.85% chance of no temptation at all.

These values show that, in order to restrict drivers from crossing the separation (even during incidents), TD is the most effective method of separation as the probability of having high temptations is the lowest. Next, the most effective method is VS strip for which the probability of having high temptations is smaller than those found for SDL and CHM.

Table 3-3: Cumulative probabilities of intensity levels for Each Separation type (Further output of MODEL B)

Temptations	Separation Type	Estimated probabilities
High temptation	SDL	0.4092
Average temptation	SDL	0.5864
Low temptation	SDL	0.7346
High temptation	CHM	0.4414
Average temptation	CHM	0.6179
Low temptation	CHM	0.7595
High temptation	TD	0.1600
Average temptation	TD	0.2804
Low temptation	TD	0.4321
High temptation	VS	0.2742
Average temptation	VS	0.4360
Low temptation	VS	0.6015

3.6 Discussion

The analysis presented in the results section shows that none of the considered variables are significant to explain actual crossing behaviour in the driving simulator. Even two traffic conditions (seeing other traffic crossing the separation or not) had no significant effect on it. The reason could be that crossing counts were not enough compared to the total number of observations. This low number of crossings can be explained by the fact that most participants were law abiding and strictly followed the traffic rules. In fact, those drivers who crossed, described different reasons for crossing. The most frequent reason was that they got irritated due to waiting in the traffic jam, which suggested that if duration were increased for the traffic jam then more participants would probably feel tempted to cross the separation. As an interesting observation, there were around 11.36% of drivers (5 participants) who crossed all separation types suggesting that once a driver crossed one separation type, he kept crossing other separations as well, irrespective of the separation type and traffic conditions. This resulted in almost similar crossing counts for TD and VS as well compared to SDL and CHM. These participants indicated in the post-questionnaire discussion that they could not wait as they were not sure how long it would take the traffic to resume. Participants were of the opinion that they perceived TD and VS as a physical barrier even though they were driving a simulated car, crossing this separation might damage their vehicle in real life.

Though separation type has no significant effect on the crossing behaviour, this factor was found prominent when temptation intensities for crossing were analysed. Results indicated that the probability of high temptations for pavement markings is significantly higher than for the two other analysed separation types. Although the actual traffic jam duration is expected to be significantly higher in reality than used in the simulator experiment, it can be assumed that the percentage of high temptations is a lower bound estimate. From the analysis of the data for both response variables (i.e. crossing behaviour and temptations for crossing) it is noted that drivers' socio-demographic background (such as gender, age, driving experience and education) were not important. This indicates that drivers who distinguish TD and VS from SDL and CHM in formulating their temptation scores are mainly doing so because of the structural and outlook characteristics of the separations. Additionally, the hypothesis that observing other vehicles crossing the soft separation might influence participant's crossing behaviour and temptations was rejected as well. This indicates that most drivers make their own evaluation in the decision whether to cross or not and consider crossing the soft separation as an illegal move.

From a practical point of view, all separation methods evaluated in this study have certain limitations. The installation cost is the lowest for pavement markings but they are the least effective in restricting drivers to their lanes as both SDL and CHM were found to have a similar effect on crossing, as well as temptations to cross. Tubular delineators have a low installation cost but they require periodic maintenance, further they physically separate two traffic flows. Similarly, VS also separates two traffic flows. In order to use a vegetation strip as separation type, it needs to be designed properly so that it does not affect the rest of the road structure negatively. For example, kerb stones can be placed on both edges of the VS along with a proper drainage system.

3.7 Conclusions

In this study, four different soft separation techniques and two traffic conditions were evaluated in a driving simulator and by means of pre and post-questionnaires. For crossing behaviour, no significant differences were found between the four soft separation techniques. However, the post-questionnaire, aimed at measuring participant's temptations to cross the separation, showed a significant difference between the different separation types in explaining the different temptation intensity levels. The analysis of temptations to cross showed that tubular delineators (TD) is the most effective soft separation technique in restricting crossing manoeuvres. VS was also found to be more effective than pavement markings (such as SDL and CHM) for the same purpose. Therefore, if flexibility is of prime importance for a certain section in express lanes and also the safety aspects cannot be neglected, both of these methods can be used.

Further research could focus on extending the duration of the traffic jam or in increasing the amount of vehicles crossing the soft separation to study if this could increase the temptation or actual crossing behaviour of drivers.

Acknowledgement

Part of this research was funded by a grant from the Higher Education Commission in Pakistan.

3.8 References

AASHTO (2011). A Policy on Geometric Design of Highways and Streets, 2011, AASHTO.

Ariën, C., et al. (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.

Ariën, C., et al. (2017). "The effect of pavement markings on driving behaviour in curves: a simulator study." Ergonomics **60**(5): 701-713.

Arien, C., et al. (2013). "A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload." Accid Anal Prev **61**: 43-53.

Ballinger, G. A. (2004). "Using generalized estimating equations for longitudinal data analysis." Organizational research methods **7**(2): 127-150.

Bella, F. (2008). "Driving simulator for speed research on two-lane rural roads." Accident Analysis & Prevention **40**(3): 1078-1087.

Bella, F. and A. Calvi (2013). "Effects of simulated day and night driving on the speed differential in tangent–curve transition: a pilot study using driving simulator." Traffic injury prevention **14**(4): 413-423.

Benedetto, C. and A. Benedetto (2002). A driving simulator based integrated approach for road geometry validation: an assessment of the road safety standards. Applications of advanced technologies in trasportation.

Brewer, M. (2014). "Operational Effects of Design of Access Points on Katy Freeway Managed Lanes in Houston, Texas." Transportation Research Record: Journal of the Transportation Research Board(2404): 9-17.

Cassidy, M. J., et al. (2015a). "A problem of limited-access special lanes. Part I: Spatiotemporal studies of real freeway traffic." Transportation Research Part A: Policy and Practice **80**: 307-319.

Cassidy, M. J., et al. (2015b). "A problem of limited-access special lanes. Part II: Exploring remedies via simulation." Transportation Research Part A: Policy and Practice **80**: 320-329.

Cooner, S. and S. Ranft (2006). "Safety evaluation of buffer-separated High-Occupancy Vehicle lanes in Texas." Transportation Research Record: Journal of the Transportation Research Board(1959): 168-177.

Davis, M. (2011). "Current industry trends for separating express lanes from general purpose lanes." White Paper. Atkins, Ltd.

Elefteriadou, L. and A. Kondyli (2009). "Driver Behavior at Freeway-Ramp Merging Areas." Transportation Research Record: Journal of the Transportation Research Board **2124**(-1): 157-166.

FHWA, U. (2010). Manual on uniform traffic control devices (2009), Baton Rouge: Claitor's Law Books and Publishing.

Fitzpatrick, K., et al. (2008). "Intermediate Access to Buffer-Separated Managed Lanes." Transportation Research Record: Journal of the Transportation Research Board(2065): 18-26.

Fuhs, C. and J. Obenberger (2002). "Development of high-occupancy vehicle facilities: review of national trends." Transportation Research Record: Journal of the Transportation Research Board(1781): 1-9.

Gómez, R., et al. (2011). "Do advance yield markings increase safe driver behaviors at unsignalized, marked midblock crosswalks? Driving simulator study." Transportation Research Record: Journal of the Transportation Research Board(2264): 27-33.

Hardin, J. W. (2005). Generalized estimating equations (GEE), Wiley Online Library.

Kuchangi, S. P., et al. (2013). Guidance for Effective Use of Pylons for Lane Separation on Preferential Lanes and Freeway Ramps.

Liu, X., et al. (2011). "Analysis of operational interactions between freeway managed lanes and parallel, general purpose lanes." Transportation Research Record: Journal of the Transportation Research Board(2262): 62-73.

Transport, D. o. (2003). Traffic Signs Manual. London, Department of Transport.

van Loon, A., Walhout, R., van der Velden, B. (2015). Verkeerskundige overwegingen bij ontvlechtingen op autosnelwegen en weggebruikers wegwijs maken. Nationaal Verkeerskunde Congres 2015.

Zorn, C. J. (2001). "Generalized estimating equation models for correlated data: A review with applications." American Journal of Political Science: 470-490.

4 Safety Comparison of Standard and Taper Designs with Decreasing Number of Lanes under Various Heavy Vehicle Compositions: A Driving Simulator Study

This study has been submitted for review:

Awan H.H., Pirdavani A., Adnan M., Yasar A., Wets G., and Brijs T. (2018). Analysis of Merging Freeways with Decreasing Number of Lanes: A Driving Simulator Study. Submitted for 2nd review: *Ergonomics*.

4.1 Abstract

Road geometric design standards provide various possibilities for merging freeways with a decreasing number of lane. In this study, two alternative designs (i.e. standard and taper) were investigated under three different heavy vehicle composition. Taper design is not preferred in the road geometric design guidelines and the designer has to provide arguments for selecting taper design. Therefore, a driving simulator was used to examine and compare the performance of these two designs under different heavy vehicle compositions. Mean speed, acceleration, standard deviation of acceleration/deceleration, and cumulative lane changes were applied to compare these two designs after merging using MANOVA and repeated measures ANOVA. Due to the geometrical differences between the two designs, the standard design was also analysed upstream of the merging point using similar parameters and statistical techniques. Results indicated that drivers' discomfort in performing merging manoeuvres was the most in case of a taper design and when heavy vehicle percentage is moderate (15%). Overall, standard design was found to be more favourable.

Keywords: Merging of freeways, taper design, heavy vehicles, vehicle compositions, driving behaviour, driving simulator

Practitioner Summary

Driving behaviour (DB) at merging freeways with decreasing number-of-lanes is under explored. We analysed safety in DB considering heavy vehicles (HV) for taper and standard designs provided in Dutch guidelines using a driving simulator. Standard design was found safer. Moderate HV presence caused more disturbances in DB.

4.2 Introduction

Freeways provide free flow of traffic at higher speeds. The merging of freeways, hence, has to be designed in such a way that its effect on the free flow is minimum. The principles underlying the safe design of road elements are widely accepted and often they are translated by local road authorities into custom road design standards e.g. PIARC (2012). As a result, different design solutions arise for the same design problem. Merging of freeways at a very small angle can be carried out either with the same number of lanes or with decreasing number of lanes. Dutch standards provide various designs to merge freeways with decreasing number of lanes as shown in Figure 4-1 (ROA 2017). The preferable method is to reduce the number of lanes either on left or right freeway before the merging point. Lane reduction from the right freeway has an extra advantage that the heavy vehicles on the main freeway have to change only one lane in order to drive in the rightmost lane. This will cause less disturbance in the traffic stream in the right lane as one lane of merging freeway is dropped before the lane reduction. The taper design is another method to merge freeways in the same manner. The standards provide a complete design of taper with respect to the design speed. However, the taper design is not preferred in Dutch guidelines and appropriate reasons have to be provided by the designer in order to justify the use of the taper design. The Dutch guidelines, however, do not specify reasons for the non-preference of taper design.

Consideration of human driving behaviour while designing road infrastructure is important as most of the accidents occur due to human error (NHTSA 2015).Therefore, it is important that human driving behaviour should be considered in the safety evaluation of road designs. However, in the sustainable safety design approach, the focus of all aspects of the transportation system (e.g. traffic, road environment, traffic rules) is the road user. Three key concepts functionality, homogeneity and predictability are included in the sustainable safety concept. Functionality is described as the similarity between the actual and intended use of the facility. Homogeneity refers to the similarities in speed,

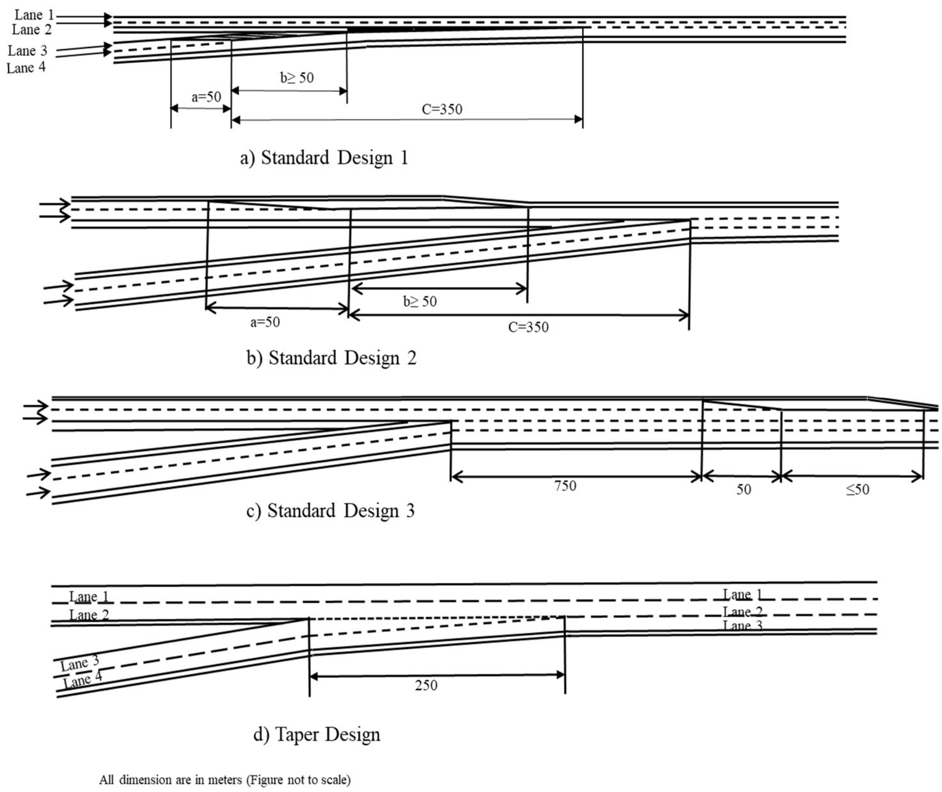


Figure 4-1: Standard and Taper designs according to Dutch Standards

direction, and the type of road users. Predictability is defined as the road design is easier to understand to the road users and they can easily recognize what kind of driving behaviour is required (Wegman et al. 2005). The concept of self-explaining roads advises that the road designs must be simple and easy to understand in order to evoke the correct behaviour in the road users (Herrstedt 2006). Based on these concepts, two road designs (standard (Figure 4-1a) and taper (Figure 4-1d)) with the same intensity to capacity (I/C) ratio were created in the driving simulator. The designs were compared with each other to find out which design can better accommodate drivers' behaviour. In this study, mean speed, acceleration, standard deviation of acceleration-deceleration (SDAD) and lateral position are considered as safety indicators of human driving behaviour. A driving simulator was used to collect data for the above-mentioned parameters as it is a safe, effective, efficient and economical approach to conduct such research. Furthermore, it was hypothesized that changes in the number of heavy vehicles may influence the human driving behaviour in the vicinity of the merging section. Heavy vehicles have been known to have an impact on the traffic stream due to their size, slow lane changing manoeuvres, low speed and acceleration/deceleration (Moridpour et al. 2015). To study the effects of heavy traffic on drivers' behaviour, three different heavy vehicle percentages less, moderate and high (0, 15 and 30%) were applied on both main and merging freeways.

4.3 Literature review

Various studies have been conducted to study driver behaviour when merging onto freeways. However, studies which investigated the safety of taper design are limited. Ruyter (2016) conducted a driving simulator study in which a taper design was compared with a design in which lane reduction takes place on the left downstream of the merging point. It could not be concluded from the results which design is safer than the other. However, it was found that taper length has a positive effect and heavy traffic had a negative effect on road safety.

AASHTO (2011) do not provide design guidelines for merging of two freeways with decreasing number of lanes. However, they provide the design of acceleration lanes as parallel and taper. Furthermore, it is mentioned in the guideline that parallel should be preferred over taper designs as it is considered safer by several road agencies in the US. Reason provided for the designer's preference of the parallel design over taper is because in taper design, if either merging vehicle abandons the merging manoeuver, existing traffic in adjacent lanes could restrict the merging vehicle from escaping to the adjacent lane (AASHTO 2011). Detailed explanation and reasoning, however, are not provided. The Dutch standards (ROA 2017) provides designs for merging of two freeways which are called as standard and taper designs. These can be seen in Figure 4-1. Among the four designs shown in Figure 4-1, three designs i.e. Figure 4-1(a), 4-1(b) and 4-1(c) are referred to as 'standard designs', where merging is done by reducing the lane either at downstream and upstream of the nose point. The fourth design (Figure 4-1(d)) is the taper design where merging and lane reduction takes place simultaneously. The Dutch standards also specify that standard designs should be preferred over the taper as they are safer. However, the underlying reasoning is not provided in detail. However, an example of an explanation for selecting the taper design is that the taper design requires less space. Hence if there are any space limitations, taper design can be used (ROA 2017).

In human factor guidelines (Woodson et al. 1992), the merging task on a freeway entrance ramp is divided into various subtasks. These tasks are separated across the given lengths of ramp and acceleration lane. For the Dutch preferred design (called standard design in this thesis: Figure 4-1a), the merging task can be divided as follows: lane changing upstream of the lane reduction, finding a suitable gap, adjust speed by accelerating/decelerating, accelerating to match the speed with traffic stream on the main freeway and then merging into the traffic stream on the main freeway after the nose point. In this way, adequate time and distance are provided to the drivers to accomplish each task. In contrast, for taper design, drivers have to perform all these tasks within 250 meters and as a result, some drivers may get confused, which increases the probability of accident occurrence (Koepke 1993).

Although literature is scarce for merging freeway designs with decreasing number of lanes, this is not the case for the acceleration lane taper and parallel design, which are studied in detail. For example, Torbic et al. (2012) studied mainline freeway ramp terminals by observing on field data, human behavior and then applied crash analysis on the data collected from field observations. The parameters used in this study to investigate driving behaviour were mean speed and acceleration. They concluded that vehicle merging speeds on taper acceleration lanes were close to the design speed of the main freeway than in parallel acceleration lanes. Several studies show that geometry of the design influences driving behaviour on acceleration lanes (Hassan et al. 2006, Ahammed et al. 2008, Hassan et al. 2012). Elefteriadou and Kondyli (2009) investigated drivers' intended actions along a freeway-ramp merging segment under various scenarios by conducting focus group sessions in which participants indicated their thinking process and possible actions while traversing a merging segment. The study considered non-congested and congested traffic conditions and also correlated the drivers' responses to their individual characteristics. They concluded that the majority of participants would speed up and be more aggressive on taper ramps compared to parallel ramps. De Blasiis and Calvi (2011) used a driving simulator to observe drivers' behavior on various acceleration lanes with varying traffic conditions. Variables used in this study were lateral position (trajectroy) of the drivers, mean speed, acceleration and number of gaps rejected. The study concluded that merging lengths of the driver, acceleration oscillations and the number of gaps rejected while merging on to the main freeway was directly proportional to the traffic volume of the main freeway. Sarvi et al. (2004) conducted a driving simulator validation study by observing the freeway ramp merging phenomenon under congested traffic conditions. Mean speed, acceleration and lateral position were also used to study driving behaviour parameters. The results indicated a significant speed reduction immediately prior to the merging maneuver into the freeway lane in all trajectories. The study also suggested that the driving simulator is a useful data collection tool and can be beneficial in the future investigation of ramp driver's merging behavior. Several other studies support the same statement (Godley et al. 2004, de Winter et al. 2009, Kircher and Thorslund 2009, Zhang and Kaber 2013, Melman et al. 2018).

Heavy vehicles are known to have an impact on the traffic stream. Heavy vehicles are classified as vehicles having gross weight more than 3.5 tons. In terms of length, heavy vehicles selected for this study were between 7.62 and 12.8 meters long. Ahmed et al. (2013) found that headways between passenger cars increased due to the presence of heavy vehicles. They also found that maximum throughput of the freeway decreased when heavy vehicle percentage increased more than 3 percent. Moridpour et al. (2015) observed that large front and rear gaps exist in a traffic stream between heavy vehicles and passenger cars due to limited maneuverability and safety concerns respectively. Their results showed that an increase in heavy vehicles percentage of up to 30% can increase the probability of crash occurrence by 5%. This shows that an increase in heavy vehicles has an adverse effect on efficiency and traffic safety.

The literature review showed that taper design is considered unsafe, however, no specific reasons are provided. Heavy vehicles are also known to influence road safety negatively. However, the threshold of heavy vehicle percentage that can be accommodated by the road designs is not provided in the Dutch standards. Based on these, objectives of this study are defined. The first objective of the study is to compare road safety of the standard and taper design by means of driving behavioural parameters. The second objective is to find out effects of different heavy vehicle percentages on driving behaviour parameters and to find out which design performs well under these circumstances.

4.4 Methodology

4.4.1 Scenario Design

In this study, a comparison was made between the standard design (Figure 4-1a) and the taper design (Figure 4-1d), both retrieved from the Dutch guidelines (ROA 2017). The motivation for selecting these two designs is that in both considered designs merging manoeuvres and lane reduction take place in almost comparable longitudinal lengths (Figure 4-1a, length= 400m; Figure 4-1d, length = 250m). In other standard design (Figure 4-1c), this longitudinal length is much higher. In this study, for the standard design in Figure 4-1a, dimension b was set to 100 meters as it is stated in the standards that this has to be greater than 50 meters.

Three virtual scenarios, with a two-lane freeway 18 KM long containing the two considered merging designs in a randomized order with three heavy traffic compositions (0, 15 and 30%), were created in a driving simulator program STISIM Drive Version 3. In each scenario, merging designs were inserted in such a way that each participant drove through both designs twice in one run. As mentioned in ROA (2017) for these designs, intensity to capacity ratio (I/C) on both merging and main freeway has to be less than 0.7. Hence, I/C ratio was kept constant at 0.6 on both freeways. According to the traffic volume given in ROA (2017) and I/C ratio of 0.6, the total number of vehicles per lane per minute for 0% heavy traffic was 24. For 15 and 30% of heavy vehicles, the total number of vehicles turned out to be 18 and 15 with 4 and 6 heavy vehicles per lane per minute respectively. Drivers were informed of a merging freeway ahead on both designs by means of a merging sign placed 550 and 400 meters before the nose point on the standard and taper design respectively.

4.4.2 Driving Simulator

The driving simulator used in this study was a medium-fidelity, fixed-base driving simulator (Figure 4-2). It consisted of an actual car (Ford Mondeo) with a steering wheel, brake pedal, clutch, and accelerator. Interior car functions such as music system, windows, GPS etc. were idle except for the turn indicators. The sound of the driver's vehicle and traffic in the environment were also present. The virtual environment was projected on a large 180 degree, seamless curved screen at a resolution of 4200 by 1050 pixels and 60 Hz refresh rate. The driving simulator was set to automatic gearbox configuration and data were collected at a frame rate.

Figure 4-2: Driving Simulator at IMOB University of Hasselt

4.4.3 Participants

A convenient sample of 52 participants with a valid driving license volunteered for this study. The participants were recruited via email to the Hasselt University staff and students. After screening for outliers, data of 49 participants (63% male, 37%

female) were used for the analysis. The outliers were identified on the basis of speed i.e. their speed was higher than the three standard deviations of the mean speed of the remaining drivers (Arien et al. 2013). Mean age and mean driving experience of the participants were 31.13 years (standard deviation = 7.3) and 10.9 years (standard deviation = 7) respectively. Each participant signed a consent form before participation. The study protocol was approved by the ethical committee of Hasselt University. Before the experimental data collection, each participant started with a warmup drive to familiarize with the driving simulator. After the experiment, participants were asked to fill out a post-questionnaire to select one of the two geometric designs at which they felt safe while driving in the simulator. They were informed about the order in which they drove their scenarios and were asked to select the proportion of heavy vehicles they felt comfortable by writing the most favourable option. In the questionnaire, percentages of heavy vehicles were mentioned as small, moderate and high corresponding to 0, 15 and 30% respectively.

4.4.4 Data Collection

Data for longitudinal speed, longitudinal acceleration and lateral position across the entire length of the scenario (18km) for all three heavy vehicle percentages were obtained from the driving simulator. From these data, 1.5 km long sections for standard and taper designs were extracted as shown in Figure 4.3. Each merging section was then further divided into 75 zones of 20m length each for analysis. As both designs are used to merge the two freeways, the most important section for comparison becomes the length downstream of the nose point. For comparison, a 360m long (18 zones) section was selected downstream of the nose point for both designs and is labelled 'Analysis Section A'. Driving behaviour parameters such as speed, acceleration/deceleration, standard deviation of the acceleration/deceleration (SDAD) and the cumulative number of lane changes (CLC) were examined to study the effects of the three heavy vehicle compositions and the two merging designs.

From lateral position data, the cumulative number of lane changes for each participant was calculated from the starting point to the end point of the 1.5km long section. CLC means that each time a participant changes lane, the lane change count increases by one. For example in the standard design, all drivers at the beginning will have CLC value of 0. Then as they progress through the section, they are required to change their lanes because of the geometrical design of the lane reduction when driving in the left lane, their CLC value will increase to 1. This CLC value is then averaged for all drivers for each zone in the 1.5km section. When they reach the nose point (Analysis Section A), their CLC value will again increase by 1 and their new CLC value will become 2. So, the possible minimum value at the nose point is one and zero for standard and taper design respectively. The difference between CLC values at the start and end of the analysis section A represents the number of lane changes occurred in that section.

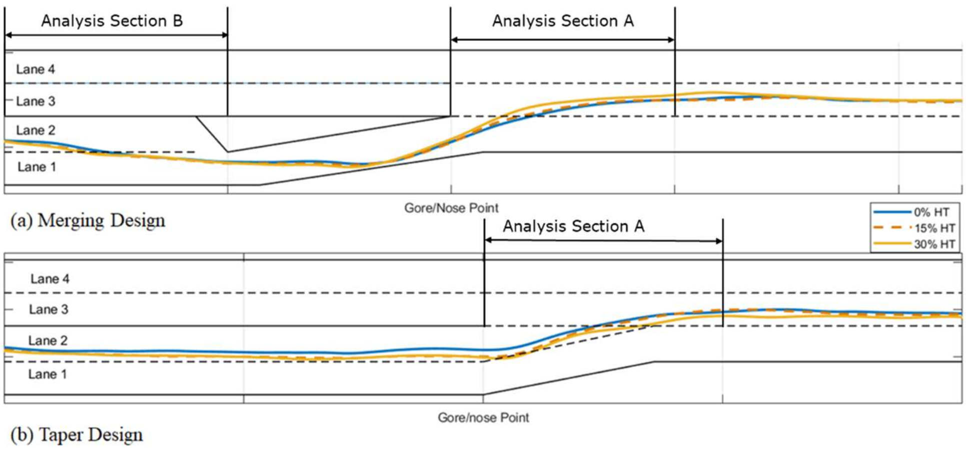


Figure 4-3: Lateral Position Profile for Standard and Taper Design

For the standard design to be safe, the lane change manoeuvre should also take place smoothly and safely. For this, a 360m long section (analysis section B) upstream of the lane reduction was defined and the effects of different heavy vehicle percentages were observed on the driving behaviour parameters.

4.5 Results and Discussion

For subjective safety, the main results from the post-questionnaire survey demonstrated that:

(1) 42 out of 49 participants (86%) felt more comfortable in less heavy traffic conditions whereas 5 (10%) and 2 (4%) participants also felt comfortable driving in moderate and high traffic conditions respectively.
(2) 30 out of 49 participants (61%) chose the standard design as safe in contrast to 19 participants (39%) who indicated the taper design as a safe option for merging of freeways.

Consequently, there is a tendency that subjective road safety is better for standard design compared to taper and also the presence of heavy vehicles is not preferred. Results from driving simulator experiment are discussed next.

4.5.1 Comparison of two geometrical designs (Analysis Section A)

In this section, the effects of different heavy vehicles percentages and two geometric designs are investigated on driving behaviour parameters, i.e. mean speed (MS), mean acceleration/deceleration (AD), standard deviation of acceleration/deceleration (SDAD), and the cumulative number of lane changes (CLC) for Analysis Section A. Multivariate analysis of variance (MANOVA) is applied to study the overall effects of the independent variables (heavy vehicles percentage and geometric design) on the dependent variables (MS, AD, SDAD and CLC) simultaneously, similar to the study from Ariën et al. (2017). Analysis section A is selected because merging manoeuvres take place after the nose point in both standard and taper designs. The effects of a two-way interaction between traffic conditions and geometric designs were also investigated. Repeated measures ANOVA was applied to investigate the effects of the independent variables on each dependent variable separately as each participant drove through all scenarios one after the another in randomized order. This is also recommended in Calvi (2015).

Table 4-1: Statistical Results For Comparison Of Merging And Taper Design

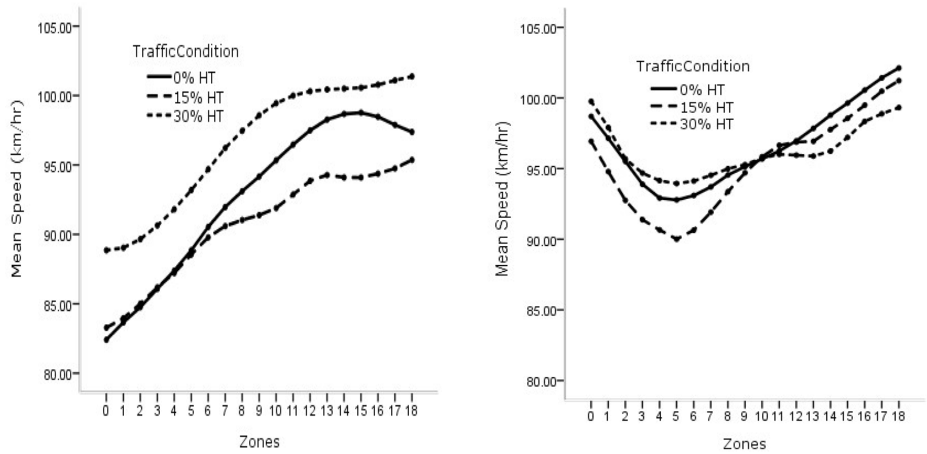
MANOVA results for comparison of merging and taper design (Wilks' Lambda)								
Independent factor	**F**				**p-value**			
Traffic Conditions	20.623				.001			
Geometric Design	498.632				.001			
Traffic Conditions * Geometric Design	9.979				.001			
Test of with-in Subject Effects (Greenhouse-Geisser)								
Independent Factor	**Speed**		**Acceleration/ deceleration**		**SDAD**		**Cumulative Lane Change (CLC)**	
	F	p-value	F	p-value	F	p-value	F	p-value
Traffic Conditions	29.837	.001	1.220	.295	6.111	.003	79.807	.001
Geometric Design	37.054	.001	53.370	.001	4.953	.026	1607.394	.001
Traffic Conditions * Geometric Design	9.691	.001	2.430	.089	5.881	.003	31.469	.001

Table 4-2: Results For Merging Design Before Lane Reduction

MANOVA results for merging design Analysis Section B (Wilks' Lambda)								
Independent factor	**F value**				***p-value***			
Traffic Conditions	8.823				.000			
Test of With-in Subject Effects (Greenhouse-Geisser)								
Independent Factor	**Speed**		**Acceleration/ deceleration**		**SDAD**		**Cumulative Lane Change (CLC)**	
	F value	***p-value***	**F value**	***p-value***	**F value**	***p-value***	**F value**	***p-value***
Traffic Conditions	19.081	.001	4.083	.018	5.761	.003	10.471	.001

Results in Table 4-1 shows that traffic conditions and geometric design, and the two-way interaction between traffic conditions and design, all have an overall significant effect on all dependent variables based on Wilks' Lambda (p-value<0.05). The significance of two-way interaction implies that for heavy vehicle composition, each variable has a different magnitude in both geometric designs. This indicates that average driving behaviour is different in all conditions of dependent variables.

To further investigate, Figure 4-4 shows the average speed profile for the standard and taper design of Analysis Section A. It can be seen that the speed profile for each traffic condition for both designs is different. From Table 4-1, this difference was statistically significant as traffic conditions, design, and the two-way interaction, all have p-values less than 0.05. In case of standard design, average speed at the nose point for 30% heavy traffic is higher than for 0 and 15% and after this point, speed for all traffic conditions start to increase. This behaviour in speed may be due to the geometry of standard design as there is a lane reduction upstream of the nose point which may cause lower values of mean speed. Mean speed is lower for 0 and 15% heavy vehicle condition due to high vehicle density compared to 30%. However, due to low density in 30% heavy vehicle condition and due to the lower speed of heavy vehicles, drivers were able to overtake most of the heavy vehicles before the lane reduction, hence before the nose point they did not have to reduce speed. Another reason for higher speed at the nose point, for 30% heavy vehicles condition could be that in this scenario drivers may have found a suitable gap for merging before the nose point (due to an overall low vehicle density on both freeways and the lower speed of the heavy vehicles). Lowest MS values were found for 15% of heavy traffic downstream of the nose point till the end of the analysis section A. This might be due to the mixed composition of passenger and heavy vehicles in this scenario and therefore, drivers were more careful.

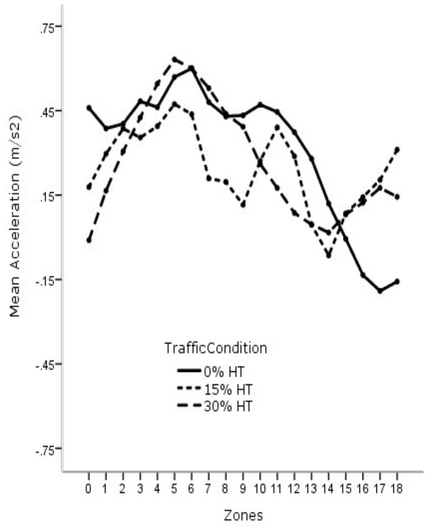


(a) Standard Design (b) Taper Design

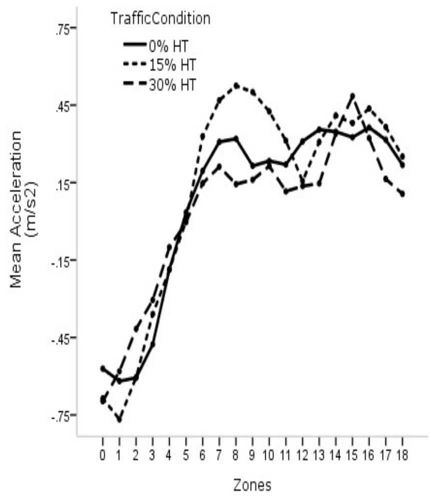
Figure 4-4: Average Mean Speed Values (Km/Hr) For Standard And Taper Design

In case of taper design, MS reduced after the nose point and continued reducing until approximately 100 meters downstream of the nose point. This is because no lane was reduced upstream of the nose point and drivers had freedom of lane choice. When drivers had arrived at the nose point, they might realize that they had to merge soon and hence, started to find gaps in the traffic from the main freeway which made them reduce their speed. MS reduction was largest for 15% heavy vehicles and was smallest for 30% due to the reasons stated above. After 100m downstream of the nose point, MS started to increase again.

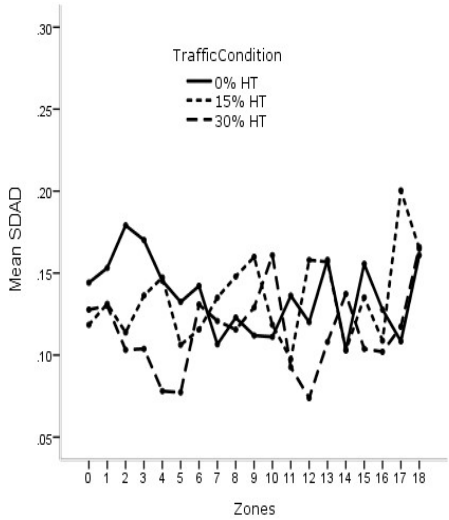
Figure 4-5a and 4-5b show the acceleration profiles for both designs in Analysis Section A. The statistical analysis showed no significant differences between the acceleration profiles for different heavy vehicle percentages (Table 4-1, p-value=0.295). The two-way interaction factor was also found to be insignificant (p-value = 0.089). Indeed, for the standard design, at the beginning of the analysis section, AD values are higher which is not surprising as speed values started to increase from this point. For the taper design, AD values for all three traffic conditions decrease at the start of the section probably because drivers realized that the merging of freeways has begun and needed to reduce their speed to find a suitable gap in the traffic stream of the main freeway.



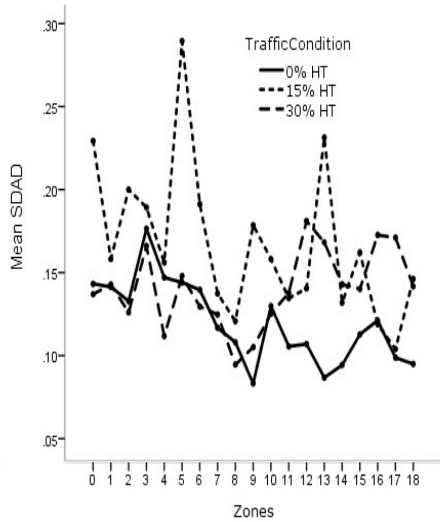
(a) Acceleration Standard Design



(b) Acceleration Taper Design



(c) SDAD Standard Design



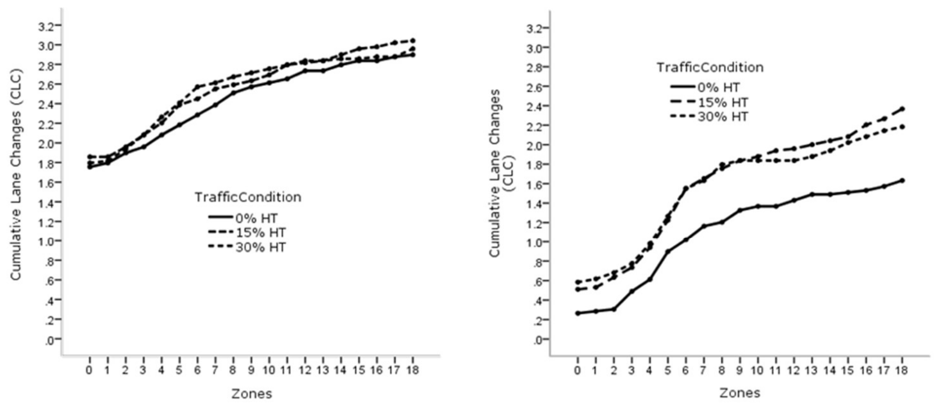
(d) SDAD Taper Design

Figure 4-5: Acceleration/Deceleration And SDAD Profiles For Standard And Taper Design

Interestingly, SDAD profiles for the standard design also show that there is little variation in SDAD (Figure 4-5c) for each of the three heavy vehicle compositions, which means that participants drove smoothly in 360 meters downstream of the nose point. However, the taper design shows much larger and statistically significant variations in SDAD (p-value <0.05, Table 4-1). In case of the taper design, SDAD variations were maximum in case of 15% heavy vehicles. For 0 and 30%, SDAD values do not show much variation. It can be assumed that drivers found it more difficult to select a suitable gap and to merge when heavy vehicle composition was 15%. This may be because, in 15%, both passenger and heavy vehicles were present in the right lane of the main freeway and gap acceptance may be difficult compared to 30% and 0% scenarios.

Figure 4-6a and 4-6b show the number of cumulative lane changes for standard and taper design after the nose point. For the standard design (Figure 4-6a), the difference between start and end of the analysis zone for 0, 15 and 30% heavy vehicles were found to be 1.14, 1.18 and 1.16 respectively. For the taper design, these values were 1.37, 1.86 and 1.60 respectively. These differences were found to be statistically significant for heavy vehicle percentages, design and the two-way interaction (Table 4-1, p-value<0.05). From the mean lateral driving profile shown in Figure 4-3a and 4-3b, it can be observed that drivers on average, merged onto the middle lane of the main freeway (lane 2 in Figure 4-1). Hence, values greater than 1 means that drivers changed lanes more than once (i.e. they switched further to the most left lane of the freeway or to the rightmost lane after merging). It was observed for both merging designs that most drivers decided to shift further to the left-most lane of the freeway (lane 1 in Figure 4-1). This is not surprising as the most right lane of the freeway (lane 3 in Figure 4-1) was more heavily occupied.

When examining the differential values of CLC for the standard design in light of values of speed, it turns out that the MS at the start of the section was less than 90km/hr, which means that participants were driving slower than the heavy vehicles. After the nose point, when they started to merge on the middle lane, they increased their speed. However, fewer variations in SDAD values throughout



(a) Standard Design (b) Taper Design

Figure 4-6: Cumulative Lane Change values for Standard and taper designs

the analysis section show that these lane changing manoeuvers took place in a safe manner i.e. without abrupt acceleration/deceleration. For the taper design, during first 80 meters downstream of the nose point, CLC values do not increase. This may be because drivers were finding a suitable gap to merge during this length. The decrease in MS during this length supports this argument. The maximum decrease in MS and larger variation in SDAD values during this length, for 15% heavy traffic shows that gap acceptance were harder when passenger and heavy vehicles were mixed. Hence, for 15% heavy vehicles, lane changing manoeuvres after merging were not executed smoothly. The difference in values of CLC for 0, 15 and 30% heavy vehicles for taper design is higher than the standard design. This shows that on average, more drivers switched to left lane after merging onto the middle lane in case of taper design when heavy vehicles were present. This also demonstrates that there is a higher number of conflict points, and hence the probability of accident occurrence in the taper design is more than the standard design.

4.5.2 Lane changing upstream of the lane reduction (Analysis Section B)

For the standard design, the lane changing manoeuvre at the point of lane reduction upstream of the nose point is also a potential zone of conflict. Therefore, effects of heavy traffic on driving behaviour parameters were also analysed in the section 360m upstream of the lane reduction point (Analysis Section B) as shown in Figure 4-3a.

From Table 4-2, based on Wilks' lambda values, it can be observed that traffic conditions have an overall significant effect on driving parameters (*p-value*< 0.05). Repeated measures ANOVA results also show the significant effect of traffic conditions on all driving behaviour parameters (*p-value*<0.05). Figure 4-7a shows MS before the final point of lane reduction. Results show that despite the absence of a speed sign, drivers reduced their speed in all three heavy vehicle composition scenarios. This reduction in MS took place because of the 'lane reduction ahead' road sign placed 400m upstream of the lane reduction. The decrease in MS was significantly different for three heavy vehicle conditions (p-value<0.05 from Table 4-2) and it was highest for 0% heavy vehicles. This might be due to the absence of heavy vehicles, which corresponds to high vehicle density. Participants in the right lane reduced their speed because vehicles from the left lane started to insert towards the right lane due to lane closure ahead. When heavy vehicles were present in case of 15 and 30%, it was easier for drivers to change lanes before lane reduction by overtaking slower heavy vehicles hence, reduction in MS was lesser.

From Figure 4-7b, it can be observed that at the beginning of Analysis Section B there was deceleration and then gradual acceleration was noted ahead. Deceleration was the highest in case of 30% heavy vehicles while it was the lowest for 15% and the gradual acceleration was the highest for 30% whereas it was the lowest for 0% heavy vehicles. However, AD values for all three traffic conditions were less than zero, meaning that drivers applied their brakes before the lane reduction. From MS (Figure 4-7a) and AD profiles (Figure 4-7b), it can be observed that drivers reduced their speed throughout this 360 meters section. Initially, they applied hard brakes, probably to find a suitable gap in the right lane and then they applied brakes slowly till they changed their lane. SDAD values (Figure 4-7c) show that there was a small variation in acceleration/deceleration for all three heavy vehicles compositions which shows that drivers reduced their speed safely. To observe the CLC, similar differential values to the ones taken for Analysis Section A were calculated for each heavy vehicle composition and were compared to each other. The difference in the start and end CLC values for 0, 15 and 30% heavy traffic was found to be 0.67, 0.81 and 0.71 respectively. Values less than 1 show that few drivers chose to drive in the right lane (lane 4 in Figure 4-1). From observations made for all four driving behaviour parameters, it is safe to assume that lane changing before the nose point for standard design took place safely and smoothly.

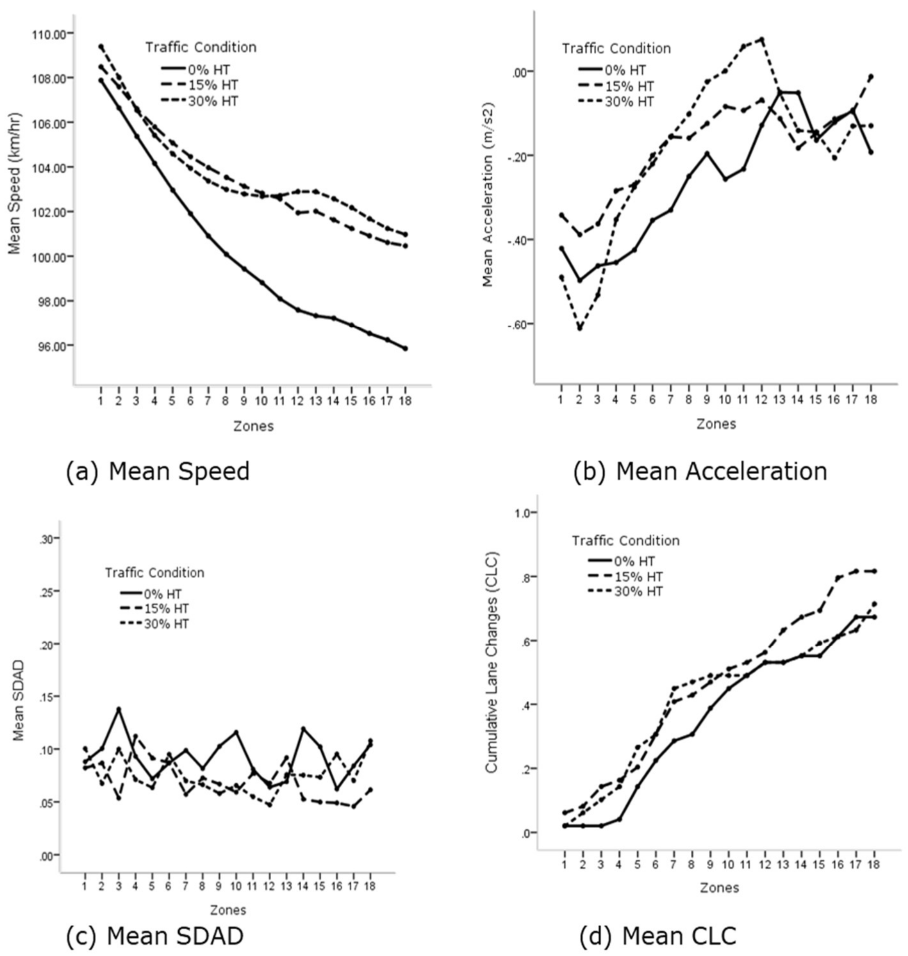


Figure 4-7: Driving Parameter Profiles for Standard Design Before Lane Reduction

4.6 Discussion

The driving simulator experiment designed by Ruyter (2016) to evaluate the safety of taper design has a number of differences when compared to our experiment. In his study, the effects of two heavy vehicle percentages (0 and 20%), and various taper lengths were analysed and compared with the standard design. However, the standard design selected for the comparison was not comparable to the taper design in terms of longitudinal dimensions and lane reduction (Standard design length 850m with lane reduction 750m downstream of the nose point vs taper design length 250m including lane reduction). Ruyter (2016) found indications from his driving simulator experiments that the taper design could be even safer than the standard design. However, this conclusion was to be interpreted with caution as a number of surrogate safety measures were not statistically different between both designs. In our study, the standard design selected for comparison with the taper design was comparable in terms of longitudinal dimensions (Standard design 400m vs taper design 250m). Our results show that the standard design is safer than the taper design. On sites where the taper design already exists, road safety can be improved by controlling lane changing manoeuvers on both the main and merging freeway using different techniques (i.e. road markings, signboards etc.) as a larger number of lane changes in the taper design increases the probability of accident occurrence. This study recommends the use of standard design for new infrastructure due to the fact that lane changing and merging manoeuvres are separated in the standard design through space and time which reduces the number of conflict points hence, reduces the probability of accident occurrence.

4.7 Conclusions and Future Research

The main purpose of this study was to investigate the driving behaviour on merging and taper designs with decreasing number of lanes according to Dutch standards and to find which of these two designs can be considered safer. Moreover, effects of different composition of heavy vehicles on road safety were studied by studying driving behaviour parameters. Results obtained for the comparison between standard and taper design for MS, AD, SDAD and CLC values show that standard design can be considered safer than taper design. Further analysis of driving behaviour parameters for the standard design before the lane reduction shows that drivers were able to switch lanes safely for all three heavy vehicle conditions. This makes the standard design more favourable and safer.

However, limitations of this study should be considered in the process of selecting a geometric design to merge freeways. Traffic intensity to capacity ratio (I/C) was intentionally kept constant at 0.6 so as to keep the traffic volume under the specified limit of 0.7 as the results could be different for other values. Moreover, effects of other driving behaviour parameters such as time-to-collision, eye and facial movements can also be studied. Comparison of the driving simulator data with real-life accident data may give more insight on which geometric design is the safest. Use of different road markings might increase the safety of taper design which can further be tested on the driving simulator before applying in the real world. Driving tests can also be performed to evaluate the safety status of each design and reveal their vulnerable elements.

Acknowledgment

Part of this research was funded by Higher Education Commission of Pakistan (HEC).

4.8 References

AASHTO (2011). A Policy on Geometric Design of Highways and Streets, 2011, Aashto.

Ahammed, M. A., et al. (2008). "Modeling driver behavior and safety on freeway merging areas." Journal of Transportation Engineering **134**(9): 370-377.

Ahmed, U., et al. (2013). "Impact of Heavy Vehicles on Freeway Operating Characteristics Under Congested Conditions." Transportation Research Record: Journal of the Transportation Research Board **2396**: 28-37.

Arien, C., et al. (2013). "A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload." Accid Anal Prev **61**: 43-53.

Ariën, C., et al. (2017). "The effect of pavement markings on driving behaviour in curves: a simulator study." Ergonomics **60**(5): 701-713.

Calvi, A. (2015). "A study on driving performance along horizontal curves of rural roads." Journal of Transportation Safety & Security **7**(3): 243-267.

De Blasiis, M. R. and A. Calvi (2011). "Driver Behavior on Acceleration Lanes." Transportation Research Record: Journal of the Transportation Research Board **2248**(-1): 96-103.

de Winter, J. C. F., et al. (2009). "Relationships between driving simulator performance and driving test results." Ergonomics **52**(2): 137-153.

Elefteriadou, L. and A. Kondyli (2009). "Driver Behavior at Freeway-Ramp Merging Areas." Transportation Research Record: Journal of the Transportation Research Board **2124**(-1): 157-166.

Godley, S. T., et al. (2004). "Perceptual lane width, wide perceptual road centre markings and driving speeds." Ergonomics **47**(3): 237-256.

Hassan, Y., et al. (2012). "Probabilistic Model for Design of Freeway Acceleration Speed-Change Lanes." Transportation Research Record: Journal of the Transportation Research Board **2309**: 3-11.

Hassan, Y., et al. (2006). Effect of Geometry of Entrance Terminals on Freeway Merging Behavior. Transportation Research Board 85th Annual Meeting.

Herrstedt, L. (2006). Self-explaining and Forgiving Roads–Speed management in rural areas. ARRB Conference.

Kircher, K. and B. Thorslund (2009). "Effects of road surface appearance and low friction warning systems on driver behaviour and confidence in the warning system." Ergonomics **52**(2): 165-176.

Koepke, F. J. (1993). "Ramp exit/entrance design--taper versus parallel and critical dimensions." Transportation Research Record(1385).

Melman, T., et al. (2018). "What determines drivers’ speed? A replication of three behavioural adaptation experiments in a single driving simulator study." Ergonomics **61**(7): 966-987.

Moridpour, S., et al. (2015). "Impact of heavy vehicles on surrounding traffic characteristics." Journal of advanced transportation **49**(4): 535-552.

NHTSA (2015). Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey, National Highway Traffic Safety Administration.

PIARC (2012). Human Factors in Road Design. Review of Design Standards in Nine Countries. La Grande Arche, Paroi nord, Niveau 2, 92055 La Défense cedex, FRANCE, World Road Association (PIARC).

ROA (2017). Richtlijn Ontwerp Autosnelwegen 2017. R. M. v. I. e. Milieu.

Ruyter, M. d. (2016). The road safety of merging tapers: Measuring the effect of varying geometric designs and traffic conditions on driving behaviour at merging tapers. Civil Engineering. Delft, TU Delft. **Maters**.

Sarvi, M., et al. (2004). "Freeway ramp merging phenomena in congested traffic using simulation combined with a driving simulator." Computer-Aided Civil and Infrastructure Engineering **19**(5): 351-363.

Torbic, D. J., et al. (2012). "Design Guidance for Freeway Main-Line Ramp Terminals." Transportation Research Record: Journal of the Transportation Research Board **2309**(-1): 48-60.

Wegman, F., et al. (2005). Sustainable Safety in the Netherlands: the vision, the implementation and the safety effects, SWOV.

Woodson, W. E., et al. (1992). Human factors design handbook: information and guidelines for the design of systems, facilities, equipment, and products for human use.

Zhang, Y. and D. B. Kaber (2013). "An empirical assessment of driver motivation and emotional states in perceived safety margins under varied driving conditions." Ergonomics **56**(2): 256-267.

5 Impact of Perceptual Countermeasures on Driving Behaviour at Curves Using Driving Simulator

This study is submitted for second review:

Awan H.H., Pirdavani A., Houben A., Westhof S., Adnan M., Brijs T. Impact of perceptual countermeasures on driving behaviour at curves using driving simulator. Submitted for review to: Traffic Injury Prevention.

5.1 Abstract

The probability of crash occurrence on horizontal curves is 1.5 to 4 times higher than tangent sections. Majority of these crashes are associated with human errors. Therefore, human behaviour at the curve needs to be corrected. In this study, two different road marking treatments, 1) optical circles and 2) herringbone pattern, were used to influence drivers' behaviour while entering the curve on a two-lane rural road section. A driving simulator is used to perform the experiment. The simulated road sections are replicas of two real road sections in Flanders. Both treatments were found to reduce speed before entering the curve. However, speed reduction was more gradual when optical circles were used. Herringbone pattern had more influence on lateral position than optical circles by forcing drivers to maintain a safe distance with the opposite traffic on the adjacent lane. The study concluded that among other low-cost speed reducing methods, optical circles are effective tools to reduce speed and increase drivers' attention. Moreover, Herringbone pattern can be used to reduce crashes on the curves, mainly for head-on crashes where the main problem is inappropriate lateral position.

Keywords: Driving Simulator, Driving Behaviour, Herringbone Pattern, Horizontal Curves, Optical Circles, Road Marking

5.2 Introduction

One of the important factors which requires due attention of the designers while designing a road section is road safety, especially in case of rural roads. According to the NCHRP report (Torbic et al. 2004), approximately 75 percent of all fatal crashes occur in rural areas. On rural roads, certain behaviour is expected from the driver which is communicated through various clues. Knowledge of drivers' perception of these clues is important as failure to comprehend these will result in unsafe situations. Weller et al. (2008) concluded that drivers classify rural roads in three different categories which can be distinguished by few objective criteria. Application of these criteria can help us design rural roads on the self-explaining principle. A road design can be considered as self-explaining when it is able to evoke the required behaviour from the drivers without the help of road signs

(Theeuwes and Godthelp 1995). With few additional road markings, a road can be made self-explanatory (Davidse et al. 2004). Their role is to inform drivers about the behaviour needed to be adopted while driving through dangerous sections.

Previous research shows that probability of occurrence of a fatal crash in curves is 1.5 to 4 times higher than that for tangent sections (Alexei et al. 2005) that makes safety a major concern in designing horizontal curves especially in rural areas. Radius of a curve is directly proportional to the design speed of the road (AASHTO 2011) and in some situations, it is required to be increased for enhancing road safety. Solutions other than changes in geometric design are required if geometry of the curves cannot be modified due to factors such as lack of available space etc. This is the case for the two selected locations in this study where altering geometric features of the curves was not feasible. According to Charlton (2007), driver's lack of attention, improper judgement of speed, poor lane positioning are major causes of driving errors that can result in crash occurrence implying the importance of appropriate curve design.

Several pavement markings at different road sections have been studied previously to make roads self-explaining (Retting and Farmer 1998, Herrstedt 2006, Daniels et al. 2010, Charlton et al. 2018). To ensure safe driving through the dangerous sections, speed reduction before entering the danger zones and maintaining the appropriate lane position is important. Charlton (2007) used various combinations of pavement markings and warning signs in a driving simulator study and found that herringbone pattern used with signboards increased the separation gap between the two opposing lanes of traffic and influences driver to follow the path that provides maximum available radius through the curve, which results in appropriate lateral position. Ariën et al. (2012) studied transverse rumble strips and herringbone pattern at curves on a two-way rural road in a driving simulator and found that transverse rumble strips were more effective than herringbone pattern in reducing speed. Kerman et al. (1982) proposed a reduction in approach speed to reduce speed at curves. This is because speed choice at curves is highly dependent on approach speed and geometry of the curve. Geem et al. (2013) used this approach of reducing speed before the entrance of the curve in their driving simulator studies by applying different treatments (e.g. sign boards, surface treatments etc.), both individually and in combination. It was concluded that the application of treatments according to the severity of curves do result in speed reduction.

Some configurations of pavement markings are presumed to manipulate speed perception of the drivers by creating an illusion of high speed, commonly called perceptual pavement markings (Meyer 1999, Rosey et al. 2008, Ding et al. 2013). Godley (1999) used optical transverse bars which gradually increased in length and width making drivers to get a feeling of increased speed while driving over them, which resulted in speed reduction. Kitamura and Yotsutsuji (2015) studied the effects of sequential transverse and lateral markings on perceived speed on a single-lane straight road using driving simulator. Different configurations of transverse markings along with roadside poles were created in which spacing between transverse markings and poles was decreasing gradually. Results indicated that the perceived speed was higher than the actual vehicle speeds. Montella et al. (2015) studied effects of transverse rumble strips, coloured strips, dragon teeth, and a coloured median along with other traffic control devices (signboards) in a driving simulator. Perceptual markings (i.e. dragon teeth, coloured strips and median) were found to have significant effect on driving behaviour both in the approach tangent and inside the curve. However, dragon teeth markings were applied in combination with the transverse rumble strips. Based on the concept of self-explaining roads and in relation to the optical markings, optical bars and dragon teeth have already been studied. However, it is required to study more innovative markings in order to develop better standards for optical markings for different scenarios such as curve section, transit areas (i.e. between rural and urban settings), danger zone etc. To augment the already existing knowledge on the effect of optical markings on driving behaviour, this study presents a novel optical marking (i.e. optical circle) to be used before horizontal curves. We hypothesize that the use of optical circles can increase drivers' vigilance and make them reduce their speed.

Previous studies mentioned above show that driving simulator is an effective tool to understand driving behaviour and study effects of other factors on it. Various other studies also used driving simulator addressing various behavioural and design related issues (Reed and Green 1999, Sarvi et al. 2004, Oron-Gilad and

Ronen 2007, Gómez et al. 2011, Antonson et al. 2013, Bella and Calvi 2013, Zhang and Kaber 2013, Bartolozzi and Frendo 2014, Bella 2014, Helland et al. 2016, Papantoniou 2017). In our study, driving simulator is used to create two horizontal curves selected from real world, and optical circles (created on the same principle as of optical bars), and herringbone pattern (used by Charlton (2007)) are applied using the similar methodology as explained in Ariën et al. (2017). The following section contains an overview of the methodology adopted for this study. This is followed by the section where obtained results are analysed and presented. These results are then discussed in detail followed by the conclusions section.

5.3 Methodology

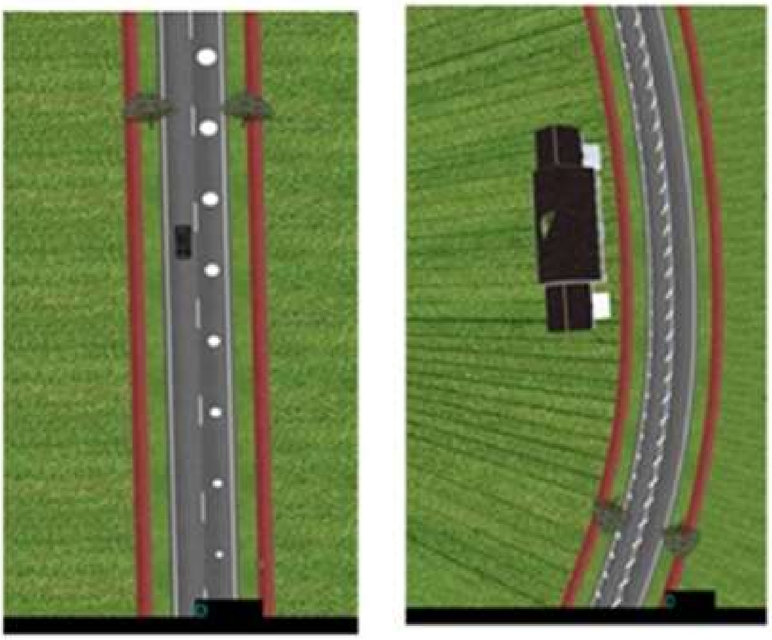
The driving simulator at the Transportation Research Institute (IMOB) of Hasselt University, is a fixed base medium fidelity simulator consisting of a mock up car (Ford Mondeo) with a seamless, curved screen placed at front of the vehicle. A synchronized image of 4200 by 1050 pixels quality is presented by three projectors at 60Hz refresh rate with 180^0 wide vision. Steering wheel, speed meter, brake, clutch and accelerator pedals and mechanisms are replaced by the digital counterparts for data collection. Vehicle sounds (simulator and traffic) were also presented. Data from the driving simulator was collected at the frame rate of 60 Hz. Previously, several road design and road marking studies (Arien et al. 2013, Ariën et al. 2014) have been conducted using the same driving simulator and its validity has been verified in Ariën et al. (2017).

Two horizontal curves (named as Hoogstraat and Masseik in this paper) selected from Belgian road network on a two-way rural road were created in STISIM Drive Version 3. Lane width on the Hoogstraat and Masseik was 3.2m and 2.8m respectively. Both of these were transitional curves and their lengths and radii are given in Table 5-2. Pavement markings i.e. optical circles and herringbone pattern were placed on both of these curves. Effects of these markings were studied by comparing both curves with a control scenario in which no treatment was applied. As a result, six road sections (three sections for each curve) were created. Length of these road sections for both curves was three kilometres and they were arranged in a randomized order to make two 18km long scenarios. The entire driving duration for both test scenarios was approximately 30 minutes.

Optical circles segment was 90 meters long with a centre-to-centre distance of 10 meters between circles. The diameter of circles increased gradually from 1.4m to 2.3m with an increment of 0.1m. Top view of optical circles in the driving simulator is presented in Figure 5-1a. The illusion of increased speed is created by the concept of forced perspective illusion according to which relation between viewing angle and distance can make objects to appear larger or smaller than their actual size (Endler et al. 2010). This optical circle segment ended 91 and 107 meters before the start of the curve for the case of Masseik and Hoogstraat respectively. Optical circles in this study are designed on the similar principal of previous studies in which transverse optical bars with gradually increasing width and decreasing distance between the markings were used to increase the perceptual speed of the drivers (Godley et al. 2000, Galante et al. 2010, Montella et al. 2011). Reason to choose circles over square and eclipse is that circles require less area than squares and eclipse will become longer if placed along its major axes in the direction of travel and might not create illusion of increased speed, or they can cover considerable portion of the lane width if placed along their major axes perpendicular to the direction of travel (Hussain 2017). Triangular road markings have already been used for various purposes such as warning signs, shark/dragon teeth markings for priority, and to keep safe distance on highways. It is assumed that it might be confusing for the drivers to understand the intended purpose of the markings if triangular markings are used in the manner similar to the previous ones. According to Dewar and Olson (2007), road markings might have negative impact on various other aspects of the road structure such as drainage, surface friction etc. Hence, the proposed treatment with circular shape is the most feasible due to their less surface area.

Herringbone pattern used by Charlton (2007) is given for 3.5m lane width. Width for the drivers to drive on both road sections was kept 2.5 meters at the start of the curve. This width gradually increases to the maximum lane width in the middle of the curve and then starts to reduce again. In this study, length of herringbone section was kept 196m for both curves. For Hoogstraat, herringbone section started 38 meters before the start of the curve and lasted 28m after the curve.

For Masseik, this section started 50 meters before the start of the curve and ended 30 meters after the curve. The inclination of herringbone strips was kept along the direction of the travel. Top view of herringbone pattern is shown in Figure 5-1b.



(a) Optical Circles (b) Herringbone Pattern

Figure 5-1: Top View of Optical Circles and Herringbone Pattern

49 participants volunteered in this study with age range between 19-54 years with mean age of 26.08 years. 28 % of the participants were female and remaining 72 % were male. Participants were invited through personal contacts of the researchers (via phone and email). They were given a brief introduction to the driving simulator and the study. After this, a warmup drive of approximately five minutes was conducted by each participant to make themselves familiar with the simulator before they drove the two scenarios of 18Km length.

Data was collected through the entire drive for both 18Km long scenarios. However, for data analysis, data from the second run was considered as we presume that the data for the second run describes more realistic driving behaviour due to the novelty effects of the first run and the potential learning effects. After detecting outliers, data for 43 participants were considered in the analysis. Driving behaviour parameters considered in this study are longitudinal speed, mean acceleration/deceleration and mean lateral position. Effects of pavement markings are computed and compared for both curves on 11 points (along the longitudinal axis) selected for the analysis. Description of these points is provided in Table 5-1. For lateral position values obtained from the driving simulator, the central median was considered as benchmark. Positive values indicate that driver is on the right side of the median.

Table 5-1: Description of All Data Points Before, At, and After The Curve

Points	
500 MBC	500 meters before the curve
300 MBC	300 meters before the curve
SOOC	Start of optical circles
EOOC	End of optical circles
SOC	Start of the curve
FQOC	1/4th of the curve
MOC	Middle of the curve
TQOC	3/4th of the curve
EOC	End of the curve
50 MAC	50 meters after the curve
100 MAC	100 meters after the curve

Table 5-2: Curve lengths and their radii

	Hoogstraat		**Masseik**	
	Curve Radius (m)	**Curve Length (m)**	**Curve Radius (m)**	**Curve Length (m)**
	170	17.21	169	51.13
	94	28.92	92	18.80
	161	45.76	97	21.28
	219	38.15	688	25.27

Table 5-3: Statistical analysis results for the curve Hoogstraat

Hoogstraat Curve

MANOVA results for Hoogstraat (Wilks' Lambda)		
Independent factor	**F value**	***p*-value**
Road Markings	206.048	.000
Points	6.636	.000
Road Marking * Points	2.077	.000

Test of With-in Subject Effects (Greenhouse-Geisser)						
Independent Factor	**Speed**		**Acceleration/ Deceleration**		**Lateral Position**	
	F value	***p*-value**	**F value**	***p*-value**	**F value**	***p*-value**
Road Markings	.185	.815	6.342	.003	.634	.488
Points	112.909	.000	91.303	.000	55.238	.000
Road Markings * Points	5.899	.000	2.108	.015	5.375	.001

Masseik Curve

MANOVA results for Masseik (Wilks' Lambda)		
Independent factor	**F value**	***p*-value**
Road Markings	10.568	.000
Points	6.636114.454	.000
Road Marking * Points	2.279	.000

Test of With-in Subject Effects (Greenhouse-Geisser)						
Independent Factor	**Speed**		**Acceleration/ Deceleration**		**Lateral Position**	
	F value	***p*-value**	**F value**	***p*-value**	**F value**	***p*-value**
Road Markings	6.265	.002	5.734	.005	12.955	.000
Points	119.579	.000	78.543	.000	45.798	.000
Road Markings * Points	3.730	.001	3.195	.000	5.463	.000

Table 5-4: Post-Hoc Analysis Results for Masseik and Hoogstraat Curves (P-Values)

	Road Marking		**Speed**	**Acceleration**	**Lateral Position**
Hoogstraat	No marking	Herringbone	0.024	0.009	0.007
		Optical Circles	0.031	0.004	0.384
	Herringbone	No marking	0.024	0.009	0.007
		Optical circles	1.000	0.04	0.021
	Optical circles	No marking	0.031	0.004	0.384
		Herringbone	1.000	0.04	0.021
Masseik	No marking	Herringbone	0.023	0.009	0.002
		Optical Circles	0.022	0.008	0.805
	Herringbone	No marking	0.023	0.009	0.002
		Optical circles	0.005	0.071	0.000
	Optical circles	No marking	0.022	0.008	0.805
		Herringbone	0.005	0.071	0.000

5.4 Results

Due to the difference in lane width of the two roads, both curves are analysed individually by applying MANOVA statistical test to study overall effects of independent variables (i.e. road marking, points, two-way interaction between road marking and points) on dependent variables (i.e. speed, acceleration and lateral position) and repeated measures ANOVA to study the with-in subject effect of independent variables on each dependent variable individually. Repeated measure ANOVA was applied due to the reason that each participant drove through all treatment conditions. Results are provided in the following paragraphs of this section. Table 5-3 present the analysis results for Hoogstraat and Masseik respectively. Road markings and points were found to have overall significant effect including the two – way interaction between them (Wilks' Lambda $p < 0.05$). This means that each road marking has significantly different values on each of the 11 points. Effects of markings are explained on all three dependent variables in this section.

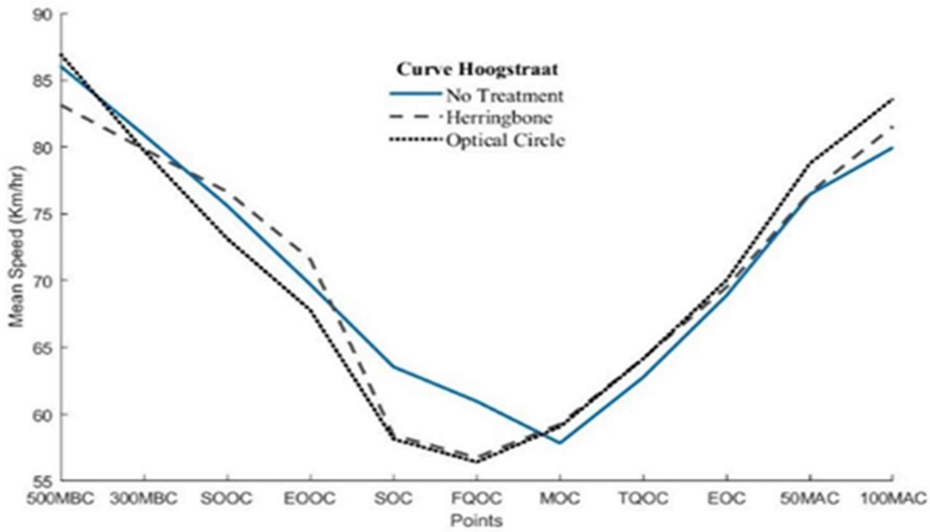
5.4.1 Mean Speed

Figure 5-3a and 5-3b show three speed profiles across the 11 points for all three conditions for the curves Hoogstraat and Masseik respectively. For both curves, there is a difference between speed profiles of three different road treatments at various points. For Hoogstraat, independent variables such as points and the two-way interaction were found significant (p-value<0.05, Table 5-3) whereas road markings turned out to be insignificant for speed (p-value=0.815, Table 5-3). Post-hoc analysis for the curve Hoogstraat shows that significant difference in mean speed was observed between the control scenario and scenarios with road markings (p-values <0.05 Table 5-4). However, difference was not significant among the two road markings (i.e. herringbones and optical circles with p-value > 0.05). For Masseik, all three independent variables had significant effect on speed (p-value<0.05, Table 5-3). Post-hoc analysis shows that for the curve Masseik, mean speed was significantly different among three scenarios (p-value < 0.05). These results show that road markings significantly reduced mean speeds before and in the curve. Drivers started to reduce their speed from the point 500 meters before the curve (500MBC) for all three conditions for both curves. The reason for this is that the curve was made visible approx. 500 meters upstream and a warning sign was placed 500m before the curve. At the Hoogstraat curve, for both treatments mean speed was decreasing until the start-of-the-curve point, however, in control condition speed kept decreasing till the middle-of-the-curve. At the Masseik curve, decrease was noted for all three conditions, and it was maximum for optical circles at the end-of-treatment point. This was expected as the objective of surface treatments is to reduce the speed of the driver before entering the curve.

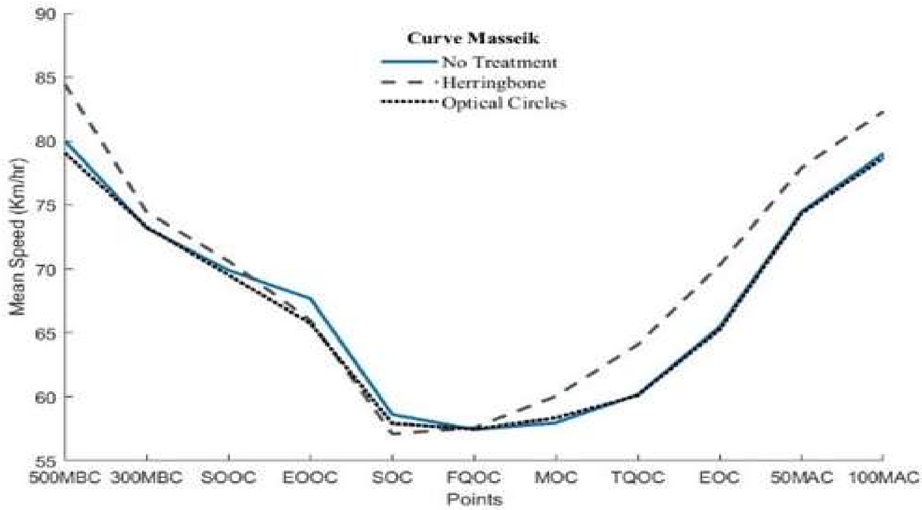
5.4.2 Mean Acceleration

Table 5-3 shows that all three independent variables were significant for acceleration at both curves (p-value<0.05). Figure 5-4a and 5-4b show the plots of mean acceleration values for all three treatment conditions across the 11 points. Difference between acceleration values among all three conditions at both curves can be seen. The post-hoc test showed that for the curve Hoogstraat, mean acceleration was significantly different among the control and the two road markings and also between the two road markings themselves (p-values < 0.05 Table 5-4). For the curve Masseik, in the post-hoc analysis, mean acceleration was found significantly different between the control scenario and the two road markings (p-value < 0.05). However, mean acceleration was not found to be significantly different between the two road markings. This shows that both road markings increased vigilance of the drivers by compelling them to decelerate well before the start of the curve. In case of Hoogstraat, the acceleration in the optical circles case drops from '500MBC' to the minimum value at start of optical circles (SOOC).

The decrease in the acceleration was gradual, which also correspond to a second order (much smoother) change in speed for optical circles case compared herringbone and control cases. For herringbones, the decrease in acceleration was constant from '500MBC' till 'SOOC'. This is because the herringbone markings



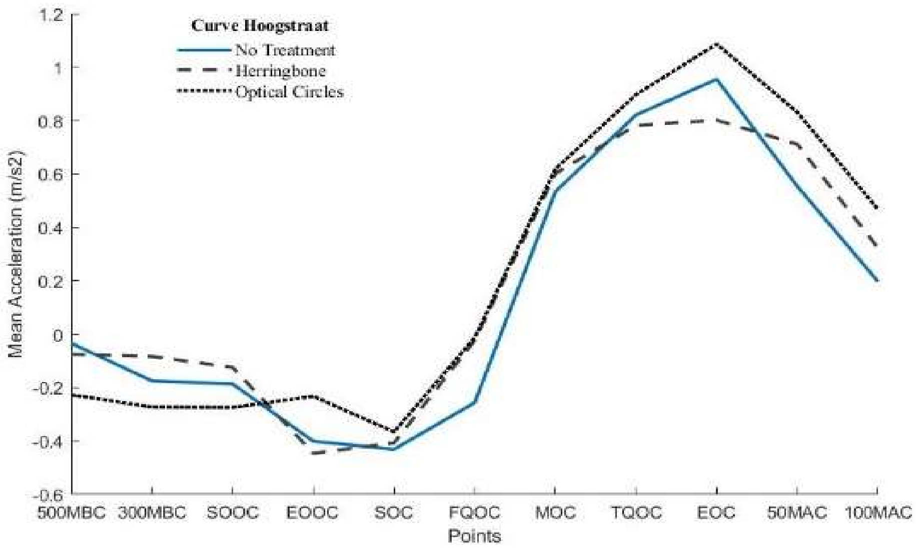
(a) Hoogstraat



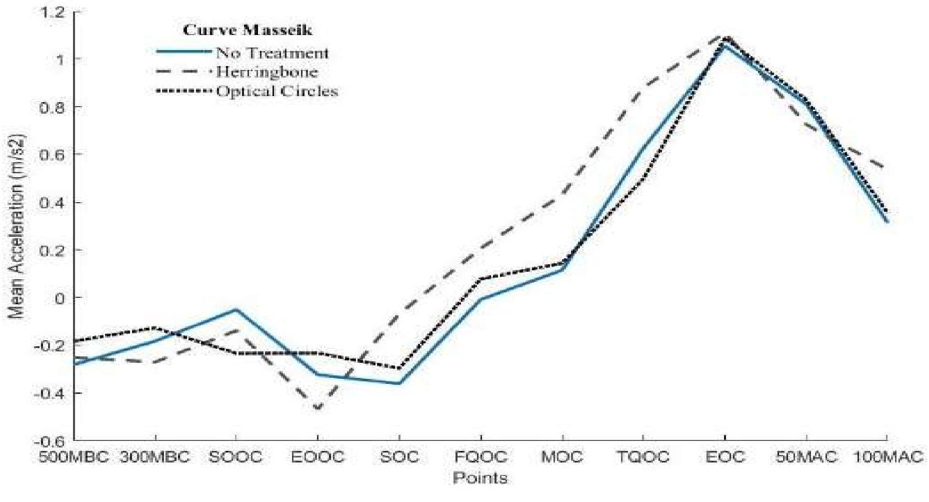
(b) Masseik

Figure 5-2: Mean speed profiles for the curves Hoogstraat and Masseik

were visible before the start of the curve. Thus, drivers reacted to those markings by decreasing their speed before the start of the curve. However, minimum acceleration values at the point end of optical circles (EOOC) imply that the drivers applied brakes over the course of 100 meters between SOOC and EOOC. In control case, acceleration values suggest that the drivers started to decelerate



(a) Hoogstraat



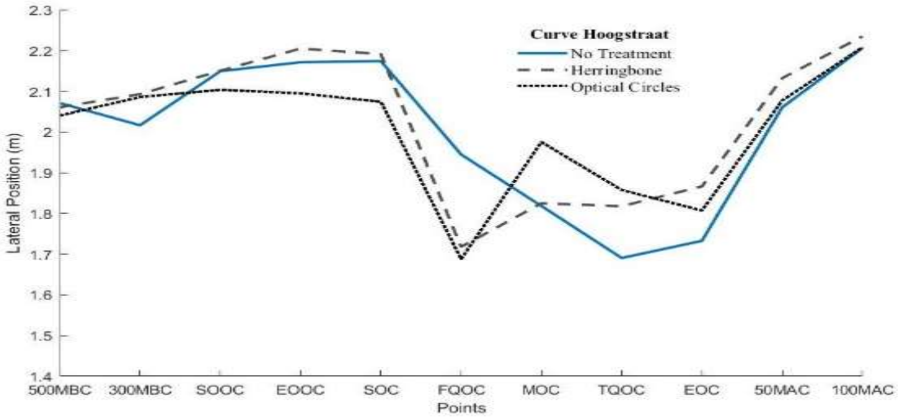
(b) Masseik

Figure 5-3: Mean Acceleration For The Curves Hoogstraat And Masseik from the point 'SOOC' and kept on decelerating till they reached the point 'first quartile of the curve' (FQOC).

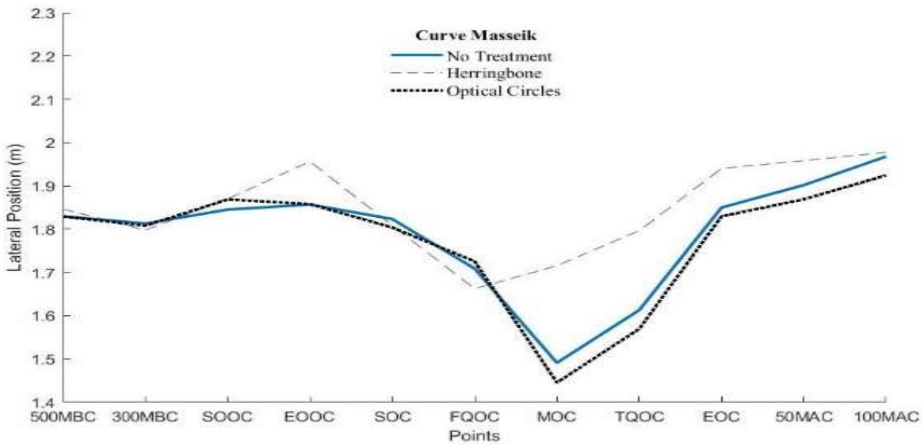
For Masseik, acceleration for optical circles was minimum at 'SOOC' point. For herringbone and control conditions, minimum acceleration values were found at the point start of the curve (SOC). Acceleration value for herringbone was smaller compared to control condition which implies drivers are braking suddenly. However, increase in acceleration through the curve was largest for the herringbone treatment. This is because, for the herringbone treatment, drivers did not have to focus on correcting their lateral position, they only required to take care of speed and acceleration. From this, we can assume that optical circles had a positive influence on speed and acceleration as they were able to reduce speed gradually. The speed did reduce for control and herringbone pattern but acceleration values suggest that speed before entering the curve was not decreased gradually rather abruptly.

5.4.3 Mean Lateral Position

Table 5-3 shows that for Hoogstraat, lateral position of the drivers are significantly different (p-value < 0.05) for points and the two-way interaction between points and road marking. The significance of the two-way interaction factor shows that values changed significantly for each road marking treatment among 11 points. This is also visible in Figure 5-5a and 5-5b. Table 5-3 shows that for Masseik, lateral position is significantly different for all three independent variables (p-value < 0.05). Lateral position values for Masseik were found to be lower than Hoogstraat. This was because of the narrower lane width of Masseik than Hoogstraat (2.8 for Masseik and 3.2 for Hoogstraat). Table 5-4 shows the post-hoc results for lateral position among the three scenarios. For both curves, significant difference in lateral position was found between herringbone and the other two scenarios (*p*-value < 0.05). However, lateral position was insignificantly different between the optical circles and the control scenario (*p*-value > 0.05). This indicates that only herringbone pattern significantly influenced the lateral position of the drivers in the curves. This is a rather predictable situation since the optical circle markings did not continue into the curve and were intended to reduce speed with no impact on lateral position.



(a) Hoogstraat



(b) Masseik

Figure 5-4: Mean Lateral Position profiles for the curves Hoogstraat and Masseik

For both curves, drivers started to adjust their lateral position from the 'SOOC' point, which is approximately 300 meters before the start of the curve, by shifting towards the right edge of the lane when herringbones were applied. Drivers adjusted their lane position by driving closer to the left side of the lane between points 'SOC' and 'FQOC' in case of Hoogstraat. For Masseik, the lateral position for all three treatments were found to be approximately similar at the 'SOC' point. In case of herringbone marking, drivers lateral position were approximately around the middle of the lane, however, for optical circles and control condition case, drivers were found to drive more towards the left edge of the lane through the curve. This might be considered unsafe as this can increase the risk of head-on collision with the traffic on the opposing lane.

5.5 Discussion

The main objective of this study was to investigate the effects of two road markings i.e. optical circles and herringbone applied before and in the curve on driving behaviour parameters using a driving simulator. In order to ensure safe driving through the curve, speed reduction should take place before drivers enter the curve as speed reduction in the curve can cause skidding of the vehicle which increases the probability of crash occurrence. Speed difference between the points 'EOOC' and 'SOC' for control condition was found to be minimum (5.33km/hr) than for herringbone and optical circles (12.23 and 8.51km/hr respectively) for Hoogstraat curve. Whereas in case of Masseik, the difference for control condition was found to be 9.07km/hr and for herringbone and optical circles, it was 8.87km/hr and 7.84km/hr respectively. This shows that both road marking treatments were able to reduce the speed of the drivers before entering the curve. Based on the concept of relative validity of the driving simulators, it can be assumed that the magnitude of the change in speed might be different in reality if same treatments are applied before and at the curve but the direction of changes would be similar (i.e. speed will decrease). For optical circles, acceleration values decreased uniformly because the optical circles were applied 100m before the curve. Acceleration values for herringbone and control condition decreased sharply before the point 'SOC'. This shows that optical circles were effective in safe reduction of speed before entering the curve. Though mean acceleration magnitude for all conditions was less than the recommended rate of -0.85m/s2 (Lamm and Choueiri 1987), it can be assumed that variations can be expected in real life, however, it cannot be said with certainty that low values of deceleration was caused due to release of the gas pedal by drivers or with the use of brake pedals. Our study also did not observe this behaviour. For herringbone pattern, acceleration values started to increase after the point 'SOC'. This is because drivers' lateral position was controlled by the herringbone markings. As a result, drivers were comfortable to drive at higher speeds through the curve.

For the lateral position, herringbones pattern's influence was significant in the curve for both Hoogstraat and Masseik. The reason for that is the path that drivers have to follow along the herringbone pattern is created in a way that the radius of the driver's trajectory is increased.

As mentioned in the literature that crash rate on curves is almost 1.5 to 4 times higher than on the straight sections and 60 to 70% of all the fatal crashes on curves are caused by single vehicle runoff (due to inappropriate speed and lateral position) (Calvi 2015). The results of our study show that by decreasing speed and modifying lateral position of the drivers, drivers' vehicle control is increased which might lead to decrease in crash rate on curves.

Ariën et al. (2017) found that for speed reduction, transverse rumble strips were more effective than the reverse herringbone pattern. In our study speed reduced for both treatments but acceleration values suggest that optical circles will cause a safe reduction in speed before the curve. For lateral position, Ariën's study did not find any significant effect of both transverse rumble strips and reverse herringbone pattern treatments before or through the curve. In our study, herringbone pattern was found to influence the lateral position of the drivers before and through the curve. This may be due to the appropriate design of the herringbone strips followed in our study. In Ariën study, herringbone strips had constant length and their inclination was also in the opposite direction of traffic flow.

Effects of optical circles on the speed reduction at curves have not been investigated previously. However, different studies did investigate the effects of optical bars on speed reduction on a straight road. In one such study, various methods to reduce speed before approaching an intersection were compared in which optical bars were compared with simple rumble strips (Montella et al. 2011). Both were found to significantly reduce the speed. Another study was conducted at the Hasselt University (IMOB) in which speed reduction at rural-urban transition due to optical bars and optical circles were studied and optical circles turned out to reduce speed more than optical bars (Hussain 2017). Results of our study give a similar outcome that optical circles are able to reduce speed safely before entering curves as compared to the herringbone pattern. A study by Montella et al. (2015), where the impact of dragon teeth were investigated on two-lane rural highways indicated that optical markings are more effective compared to other combination of road markings to reduce speed at the curve entry. They noted reduction of 12 km/hr at the curve entrance in comparison with do nothing case (the mean speed of drivers before the curve section was 110 km/hr). In our study, although the optical circle marking are found effective and significant reductions of speed were noted, the results cannot be directly compared with this study since in our case the design speed before the curve is 70 km/hr. At the entry of the curves reductions of 3-4 km/hr are noted compared with control scenario. Our study further strengthen the case for the use of optical marking as it influence the operating speed on the curves.

Road markings can be considered as relatively low-cost alternatives than other speed perceptual treatments such as road-side fence and gantry treatments to create road narrowing effect and increase drivers attention. However, according to Dewar and Olson (2007), such road markings/treatments can have drawbacks like lower drainage, lower tire to road surface friction, noise etc. Similar drawbacks can be anticipated for optical circles when implemented in real life. Hence in order to use optical circles at curves, proper engineering considerations and selection of suitable material to install optical circles can reduce such negative impacts. Herringbone pattern used in this study was found to have a significant effect on the lateral position. However, herringbone pattern used in combination with other speed reducing treatment might result in speed reduction together with better lateral position along the curve.

5.6 Conclusion

Results obtained for driving behaviour parameters show that both optical circles and herringbones have positive effects on driving behaviour. The optical circles caused safe speed reduction before entering the curve which makes them a more suitable option than herringbone pattern. However, for lateral position, herringbone pattern made drivers follow a safe path along the curve. This shows that herringbone pattern can significantly reduce the number of head-on crashes on the curves where crashes occur mostly due to faulty lateral position of the drivers. Hence, it can be concluded that at curve sections where speed reduction is required, optical circles are better option whereas herringbone pattern is more useful when inappropriate lateral position is the known cause of crash occurrence. Real world implementation of both treatments with before and after studies can allow policy makers to study the long term effects of both treatments. Moreover, comparison of other perceptual treatments and their combination (e.g. combination of herringbone pattern and optical circles) using a driving simulator may also be investigated in future.

Acknowledgment

Part of this research was funded by Higher Education Commission (HEC), Pakistan.

5.7 References

AASHTO (2011). A Policy on Geometric Design of Highways and Streets, 2011, Aashto.

Alexei, R. T., et al. (2005). SAFETY IMPACT OF EDGE LINES ON RURAL TWO-LANE HIGHWAYS.

Antonson, H., et al. (2013). "Crash barriers and driver behavior: A simulator study." Traffic injury prevention **14**(8): 874-880.

Ariën, C., et al. (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.

Ariën, C., et al. (2012). "The effect of pavement markings on driving behavior in curves: A driving simulator study." Transportation Research **13**: 14.

Ariën, C., et al. (2017). "The effect of pavement markings on driving behaviour in curves: a simulator study." Ergonomics **60**(5): 701-713.

Arien, C., et al. (2013). "A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload." Accid Anal Prev **61**: 43-53.

Bartolozzi, R. and F. Frendo (2014). "Definition of Simulated Driving Tests for the Evaluation of Drivers' Reactions and Responses." Traffic injury prevention **15**(3): 302-309.

Bella, F. (2014). "Driver performance approaching and departing curves: driving simulator study." Traffic injury prevention **15**(3): 310-318.

Bella, F. and A. Calvi (2013). "Effects of simulated day and night driving on the speed differential in tangent–curve transition: a pilot study using driving simulator." Traffic injury prevention **14**(4): 413-423.

Calvi, A. (2015). "A study on driving performance along horizontal curves of rural roads." Journal of Transportation Safety & Security **7**(3): 243-267.

Charlton, S. G. (2007). "The role of attention in horizontal curves: a comparison of advance warning, delineation, and road marking treatments." Accid Anal Prev **39**(5): 873-885.

Charlton, S. G., et al. (2018). "Using road markings as a continuous cue for speed choice." Accident Analysis & Prevention **117**: 288-297.

Daniels, S., et al. (2010). "Additional road markings as an indication of speed limits: results of a field experiment and a driving simulator study." Accid Anal Prev **42**(3): 953-960.

Davidse, R., et al. (2004). "The effect of altered road markings on speed and lateral position." SWOV Institute for Road Safety Research, The Netherlands.

Dewar, R. and P. Olson (2007). Human factors in traffic safety. Tucson: Lawyers & Judges Publishing Company, Inc.

Ding, H., et al. (2013). "Experimental research on the effectiveness of speed reduction markings based on driving simulation: A case study." Accident Analysis & Prevention **60**: 211-218.

Endler, J. A., et al. (2010). "Great bowerbirds create theaters with forced perspective when seen by their audience." Current Biology **20**(18): 1679-1684.

Galante, F., et al. (2010). "Traffic calming along rural highways crossing small urban communities: Driving simulator experiment." Accident Analysis & Prevention **42**(6): 1585-1594.

Geem, C. V., et al. (2013). Speed adaption control by self-explaining roads (SPACE). Road safety on four continents: 16th international conference.

Godley, S. T. (1999). A driving simulator investigation of perceptual countermeasures to speeding, Monash University Melbourne,, Australia.

Godley, S. T., et al. (2000). "Speed reduction mechanisms of transverse lines." Transportation human factors **2**(4): 297-312.

Gómez, R., et al. (2011). "Do advance yield markings increase safe driver behaviors at unsignalized, marked midblock crosswalks? Driving simulator study." Transportation Research Record: Journal of the Transportation Research Board(2264): 27-33.

Helland, A., et al. (2016). "Evaluation of measures of impairment in real and simulated driving: results from a randomized, placebo-controlled study." Traffic injury prevention **17**(3): 245-250.

Herrstedt, L. (2006). Self-explaining and Forgiving Roads–Speed management in rural areas. ARRB Conference.

Hussain, Q. (2017). The impact of perceptual countermeasures on driving behaviour in rural-urban transition road segments: A driving simulator study. IMOB. Hasselt, Belgium, UHasselt Belgium. **Masters of Transportation**.

Kerman, J., et al. (1982). Do vehicles slow down on bends? A study into road curvature, driver behaviour and design. Planning & Transport Res & Comp, Sum Ann Mtg, Proc.

Kitamura, K. and H. Yotsutsuji (2015). "An Experimental Study on the Effect of Sequential Transverse and Lateral Markings on Perceived Speed on a Single-lane Straight Road." Journal of Ergonomics S. 2015;**3:2**.

Lamm, R. and E. Choueiri (1987). "A design procedure to determine critical dissimilarities in horizontal alignment and enhance traffic safety by appropriate low-cost or high-cost projects."

Meyer, E. (1999). "Application of Optical Speed Bars to Highway Work Zones." Transportation Research Record **1657**: 48-54.

Montella, A., et al. (2011). "Simulator evaluation of drivers’ speed, deceleration and lateral position at rural intersections in relation to different perceptual cues." Accident Analysis & Prevention **43**(6): 2072-2084.

Montella, A., et al. (2015). "Effects of traffic control devices on rural curve driving behavior." Transportation Research Record: Journal of the Transportation Research Board(2492): 10-22.

Oron-Gilad, T. and A. Ronen (2007). "Road characteristics and driver fatigue: a simulator study." Traffic injury prevention **8**(3): 281-289.

Papantoniou, P. (2017). "Structural equation model analysis for the evaluation of overall driving performance: a driving simulator study focusing on driver distraction." Traffic injury prevention(just-accepted): 00-00.

Reed, M. P. and P. A. Green (1999). "Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task." Ergonomics **42**(8): 1015-1037.

Retting, R. A. and C. M. Farmer (1998). "Use of pavement markings to reduce excessive traffic speeds on hazardous curves." ITE journal **68**: 30-41.

Rosey, F., et al. (2008). "Impact of perceptual treatments on lateral control during driving on crest vertical curves: a driving simulator study." Accid Anal Prev **40**(4): 1513-1523.

Sarvi, M., et al. (2004). "Freeway ramp merging phenomena in congested traffic using simulation combined with a driving simulator." Computer-Aided Civil and Infrastructure Engineering **19**(5): 351-363.

Theeuwes, J. and H. Godthelp (1995). "Self-explaining roads." Safety science **19**(2): 217-225.

Torbic, D. J., et al. (2004). "A guide for reducing collisions on horizontal curves." NCHRP Report **500**(7).

Weller, G., et al. (2008). "Behaviourally relevant road categorisation: a step towards self-explaining rural roads." Accid Anal Prev **40**(4): 1581-1588.

Zhang, Y. and D. B. Kaber (2013). "An empirical assessment of driver motivation and emotional states in perceived safety margins under varied driving conditions." Ergonomics **56**(2): 256-267.

6 Conclusions and Future Research

The main purpose of the thesis is to investigate the safety of new infrastructure design based on the concepts of sustainable safety and self-explaining roads using driving simulator. Use of driving simulator in such studies can aid road safety audit process during pre-construction stages of the infrastructure projects. Furthermore, driving simulator studies can also help in analysing the perceived or subjective safety of the road designs.

Three driving simulator studies were conducted on three different discontinuities in the road design. In the first study, solid double line, cross hatch marking, tubular delineators and vegetation strip were used as separation methods to separate express lanes with local lanes. Their safety was analysed based on drivers' crossing behaviour and their temptations to cross which was obtained by means of lateral positions measurements from driving simulator and post-questionnaire filled by each participant immediately after the experiment. In second study, two merging designs for merging of freeways were studied in detail. A standard design and a taper design was created in a driving simulator according to the Dutch guidelines. Based on the concepts of sustainable safety and self-explaining roads, effects of these designs were investigated on the human driving behaviour. In the third driving simulator study, effects of pavement markings on the drivers' behaviour were investigated while driving through a curve. Two pavement markings, optical circles and herringbones were applied before and during the curve. Table 6-1 provides summarized results of all of the three studies. Details about the methodology and results obtained for each study are provided in the chapters 3, 4 and 5 respectively.

The results obtained from the fore – mentioned driving simulator studies will help policy makers and road authorities in decision making as the results provide insight into the effects of different road designs on driving behaviour. The results can also help the designers in making design self – explanatory. Based on the results, each study is concluded along with its scope and then discussion is provided for their policy implications in conclusion section 6.1 of this chapter.

Following this, aspects of future research are provided in section 6.2. Limitations of this thesis are discussed in section 6.3.

6.1 Conclusions

In general, conclusions derived from three case studies show that both of the general objectives of the study are successfully achieved. This conclusion is deduced because in all three case studies, road designs created in the driving simulator environment were not created in the real world and have not been investigated previously for similar purpose. Moreover, driving simulator ensured the active participation of common drivers in the safety evaluation process. Data obtained as a result helped in evaluation of the designs. This resulted in finding solutions for the problems investigated in this thesis and increasing the safety of the road designs.

In our first case study about separation of express and local lanes (Chapter 3), the separation methods compared are not previously studied as separation methods to provide an escape route in case of traffic jams and simultaneously restrict drivers from unauthorized lane changes between express and local lanes and vice versa. In this study, driving simulators allowed participants to experience the most realistic experience of a traffic jam. This helped the participants in describing their temptations to cross for each separation method in the post-questionnaire filled immediately after completion of the experimental drive. Conducting this study without driving simulator would have not allowed drivers to actually experience the traffic jam. The drivers would then have to answer the questionnaire based on their past experience. It might have been difficult to ensure that each participant has clearly understood the context and the circumstances for which study was being carried out.

In the second case study about merging freeways with decreasing number of lanes (Chapter 4), both standard and taper designs were previously not compared with each other under different compositions of heavy traffic. The driving simulators

Table 6-1: Overview of the key findings of all three driving simulator studies

Study	Drivers	Methodological design	Key findings
Chapter 3	49	Separation of express and local lanes • Four separation types solid double line, cross hatch marking, tubular delineators, and vegetation strip were compared with each other. • Two conditions one with and one without crossing of the vehicles were tested. • Within subject design • Generalized estimation equation (GEE) with logit function	Probability of high temptations to cross were found in the following order. Solid double line > Cross hatch marking > Vegetation strip > Tubular delineators.
Chapter 4	49	Merging of Freeways according to Dutch standards • Standard vs taper design; • three heavy traffic compositions (0, 15 and 30%); • within subject design; • analysis Zone; • MANOVA and Repeated measures ANOVA.	Standard design was found safer than taper design. Merging manoeuvres were not safe according to human behaviour parameters when heavy traffic was moderate (15%).
Chapter 5	49	Perceptual markings at curves • Optical circles and Herringbone pattern. • Within subject design • Analyse point • MANOVA and Repeated measures ANOVA.	Optical circles are useful in reducing speed before entering the curve. Herringbone pattern significantly improved the lateral position of the drivers through the curves.

allowed us to create custom designs as specified in the design standards without any space restrictions for experimentation. This allowed us to present both merging designs to the participants in the most effective way. Data for various driving behaviour parameters were collected which provided basis for the evaluation of the designs which are not yet constructed in real world.

In the third case study regarding perceptual markings at curves (Chapter 5), driving simulators allowed us to test the two road markings at two different curves. The road markings investigated in the study optical circles and herringbone pattern, are yet to be implemented in the real world especially before horizontal curves. The study provides the designers with an idea of what kind of behaviour can be expected from the drivers when implemented in the real world. The driving simulators provided us with data which we were then able to analyse and make conclusions. Overall, we can conclude with much confidence that driving simulator is indeed a useful tool to analyse different road designs in relation to human driving behaviour in pre-construction stages of the road designs.

6.1.1 Simulator Study 1

In our first case study (Chapter 3), four different soft separation techniques namely solid double line (SDL), cross hatch marking (CHM), tubular delineators (TD) and vegetation strip (VS), along with two traffic conditions were evaluated in a driving simulator and by means of pre and post-questionnaires. A traffic accident was simulated on the express lanes causing a traffic jam on express lanes. The duration of traffic jam was between 2 – 3 minutes (depending upon the speed of the test subject). Participants were asked to rate their temptations to cross the separation to local lanes as high, moderate, low and none when no vehicle from the simulated traffic jam crossed the separation and when one of the vehicles crossed the separation.

Key findings: Results showed that probability of high temptations is higher for the pavement marking methods solid double line and cross hatch marking (40 and 44% respectively). Probability for high temptation was 26% for VS and it is found lowest for TD (i.e. 16%). Hence, the study concluded that TD is the most effective soft separation technique in restricting crossing manoeuvres. VS was also found to be more effective than the pavement markings (such as SDL and CHM) for the same purpose. This was because of the fact that tubular delineators and vegetation strip both are perceived as a physical barrier separating the two types of lanes. Therefore, if flexibility is of prime importance for a certain section in express lanes and also the safety aspects cannot be neglected, both of these methods can be used.

Policy implications: There may be some complications in operation of these methods that can also be considered before making implementation decisions. For example, tubular delineators can cause increase in road debris and requires regular cleaning and maintenance. For the vegetation strip to be used as separation method, proper drainage system also needs to be designed. Furthermore, we have assumed in our study that type of vegetation used is grass with height is not more than the ground clearance height of a passenger car (approximately 10 to 15 cm). This suggests that periodic maintenance of the grass will also be required. Nevertheless, the study provides designers with theoretical knowledge regarding the separation methods and their possible effects on human behaviour that can be used to separate express and local lanes.

6.1.2 Simulator Study 2

The second case study (Chapter 4) was conducted to investigate the driving behaviour on merging and taper designs with decreasing number of lanes in Dutch standards and to find which of these two designs is relatively safer than the other. Moreover, effects of three composition of heavy traffic (low, medium and high corresponding to 0, 15 and 30%) on road safety were studied by studying driving behaviour parameters. Mean speed, acceleration/deceleration, standard deviation of acceleration deceleration (SDAD), and cumulative lane changes were the parameters defining the driving behaviour. For driving behaviour to be considered safe during the merging manoeuvre, it was assumed that there will be no sudden changes in mean speed, acceleration/deceleration, and SDAD values. Cumulative lane changes were also supposed to be as minimum as possible (minimum possible value of 1 for standard design and 0 for taper design).

Key findings: Comparison between the standard design and the taper design lead to the conclusion that standard design is safer than the taper design. This is because for standard design, there were less variations in speed and acceleration values. Cumulative lane change values for standard design were also relatively lower than in taper design. Heavy traffic composition was found to have negative impact on driving behaviour parameters. However, these negative impacts were maximum when heavy traffic composition was moderate (15%). With mixture of passenger cars and moderate level of heavy vehicles, they were more hesitant in making manoeuvring decisions. This is prominent from the driving behaviour parameter results. The results from this study provide more reasons that can augments the statements in the road design standards (e.g. AASHTO and Dutch Standard) where more preference is given to standard design.

Policy Implications: Though the study concluded that the standard design is safer, the standard design requires more longitudinal space to be constructed than the taper design. Due to space limitations, if the road designer insists on taper designs, it should be properly equipped with traffic signage, restrictions on speed limitations and lane markings that restrict unnecessary lane changes. Length of the taper should be selected in relation to the design speed mentioned in the road design standards.

6.1.3 Simulator Study 3

In the third case study conducted in this research (Chapter 5), effects of perceptual road markings were studied in a driving simulator. Optical circles and herringbones were the two methods used before and in the curve to investigate their effects on speed and lateral position of the drivers. Optical circles were placed before the curve and herringbones were placed in the curve.

Key Findings: Results show that both optical circles and herringbone markings were found to have positive impacts on speed and lateral position of the drivers. The optical circles are suitable for curves where major cause of crash occurrence is high speed and herringbone pattern is suitable for the curve section where the major cause of crash is faulty lateral position. Based on the concept of relative validity, different values can be expected if implemented in the real world.

However, the results will be in the same direction i.e. decrease in mean speed and acceleration.

Policy Implications: Before and after studies for the proposed pavement markings can provide designers further insights regarding the driving behaviour at curves. Furthermore, material for applying optical circles and herringbone pavement marking should be selected with great care. This is because these pavement markings use larger area than usual. This might have negative impact on other characteristics of road surface such as surface friction, surface drainage etc.

In general, the three case studies conducted in this research point towards the fact that the driving simulator approach is feasible to evaluate safety of the road designs during the design phase of the project and its inclusion in the road safety audits in pre-construction stage will significantly increase the safety of the road design. Of course, it might increase the time period of the road safety audits process but it can be considered as an investment as it can save additional time and resources which would be lost due to otherwise an unsafe road design.

6.2 Future Research

The three case studies helped to achieve the general objective of the thesis which was "to investigate the usefulness of driving simulation for the evaluation of road designs on the basis of human factors in order to achieve a better road design afterwards and as a consequence to improve road safety of new road designs". However, consideration of various other aspects can further improve the safety standards of the designs investigated in this thesis.

Simulator Study 1: For the separation of express and local lanes, various other possible solutions can be tested in the driving simulator before their implementation in the real world. This will provide the drivers' perception regarding those methods. Increase in waiting time during the traffic jam and increasing the number of crossing vehicles from the queue might increase temptation levels of the drivers. In addition to the post questionnaire, use of eye tracker and recording facial movements can provide us with the quantitative data regarding the temptation levels of the drivers during the traffic jam. Cost-benefit analysis can also be performed among various method of separations. This can provide more conclusive insights for recommending the type of soft separation in such cases.

Simulator Study 2: In case of merging of freeways using standard and taper design, there are many promising prospects for future research. For example, intensity to capacity ratio (I/C) was intentionally kept 0.6 whereas the maximum limit for consideration of these designs given in the standards is 0.7. Increasing the amount of overall traffic may provide different results. Using various lane markings for regulating the lateral lane movements can increase the safety of the taper design. This can also be tested in the driving simulator before implementing in the real world. Cost-benefit analysis can provide further insights to the designer in selection of the road design. Comparing driving simulator data with real life accident data and benefit to cost ratio may provide further insights regarding which design is safe. Use of eye tracker and time to collision (TTC) data can help in analysing the drivers' behaviour during merging with respect to the amount of traffic and the type of vehicle (passenger car or heavy vehicle) present in the adjacent lanes.

Simulator Study 3: For the effects of perceptual markings at curves on the driving behaviour, various other perceptual markings such as optical bars can be compared with optical circles in a driving simulator. Furthermore, effects on speed reduction and lateral position can be studied by using both optical circles and herringbone pattern simultaneously and the comparison can be made with the results of this study. Real life before and after studies can help in validating the results obtained from the driving simulator studies in terms of absolute validity.

6.3 Limitations

All experimental studies have some limitations. This is because experiments are conducted in the most possible controlled environment and there are always some assumptions associated with the experimental techniques and apparatus. There are some limitations associated with this thesis as well. These are discussed as following.

- In order to create a safe design, perspective of all road users is very important. In this study, only car drivers are considered. This is because the driving simulator program at Transportation Research Institute (IMOB) was configured according to the characteristics of a car. Perspective of heavy vehicle drivers is also very important to be considered in road design. This is because of difference of size and moving properties between heavy vehicles and passenger vehicles. Usually, the driving simulator program requires some changes to be made in configuration such as height of vision, position of rear view mirrors on the screen etc., for providing experience of driving in a heavy vehicle. Because of the time restrictions, the three road designs were analysed only from the car driver's perspective .
- Road environment in all scenarios created for the three case studies was created according to the Belgian/European road environment. Changes may be required in the road environment of the scenarios according to the local road environment if studies are conducted in another country/continent.
- The scenarios created for the three case studies in this thesis presented a rural environment to the drivers. This is because the two case studies investigated (merging of freeways and separation of express and local lanes) road designs of motorways/freeways. The perceptual road markings studied in this thesis for horizontal curves can also be studied for horizontal curves in an urban environment.
- Traffic generation in the driving simulator program used in this thesis was also very challenging. This was because each vehicle needs to be inserted individually. Making an algorithm for creation of vehicles or integrating micro-simulation program for vehicle generation can also facilitate the researchers in the process of scenario creation.
- The drivers participated in the study were also in possession of a European driving license. Participants from other geographical area may have different driving behaviour. Hence, different results can be expected if studies are conducted in locations other than Belgium/Europe.
- Selection of participants from different age groups and comparison among various age groups may also effect the results. In this thesis, the average

age of participants was between 25 and 35 years. Younger or older participants might affect the results.

- Convenient samples of participants were considered in this thesis. Participants were invited via email and personal contacts of the researcher. This can influence the duration of the experimentation as a local researcher might complete the data collection process in a relatively shorter time period than a non-local researcher.
- As all of the road designs studied in this thesis are investigated before their implementation in the real world, before and after studies, comparison between driving simulator data and real life data, and cost benefit analysis might be explored in future.