The road safety of merging tapers

Measuring the effect of varying geometric designs and traffic conditions on driving behaviour at merging tapers

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Challenge the future

THE ROAD SAFETY OF MERGING TAPERS

MEASURING THE EFFECT OF VARYING GEOMETRIC DESIGNS AND TRAFFIC CONDITIONS ON DRIVING BEHAVIOUR AT MERGING TAPERS

by

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in partial fulfillment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology,

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PREFACE

This report with the title "The road safety of merging tapers" is the final part of my Civil Engineering master on the TU Delft, Transport & Planning track. This master thesis has been performed in collaboration with the Dutch engineering company Witteveen+Bos. After my internship at Witteveen+Bos, I worked a few months parttime at the company in Amsterdam. During this period, I was asked to translate a thesis proposal about the road safety on merging tapers, that would be sent to the Transport & Planning department. The topic excited me because of it's combination of scientific and social relevance, a close relation with practice and the possibility to use an innovative driving simulator. Therefore, I proposed to start my master thesis on this subject by myself.

The use of the driving simulator, and the development of the driving simulator during the study, made this study very interesting and alternating. The innovative approach gave rise to some challenges, and several important choices were made during the study. To overcome these challenges and make wise choices during the process, the help of my committee was essential. I want to thank my professor Marjan Hagenzieker for her guidance, and for providing clear comments which were very useful in the remainder of the study. I want to thank my daily supervisor Haneen Farah for bringing over her knowledge about designing experiments and statistics, reviewing my report multiple times and always being available for ideas and discussion. I want to thank my daily supervisor Aries van Beinum for his clear comments and advices, discussing the report's structure, and of course making it possible to perform this study in collaboration with Witteveen+Bos. I want to thank my external supervisor Riender Happee for bringing over his extensive knowlegde of driving simulators. I want to thank Paul Wiggenraad for his suggestions and ideas in the first months of my work.

Furthermore I would like to thank my colleagues at Witteveen+Bos for facilitating a pleasant working atmosphere. I want to thank the colleagues which were involved in the driving simulator development for helping me building up the experiment, and overcoming challenges linked to the driving simulator.

Last but not least, I especially would like to thank my parents for their constant support in my study, for their patience and for keeping confidence in my work.

Amsterdam, November 2016

SUMMARY

In the design process for building or rebuilding motorways in the Netherlands, road designers have the freedom to vary between different design options. One of the road segments where this is the case, is at mergers. A merger is defined as a convergence point of two roadways with a similar design speed, and for both roadways holds that at least one of the lanes continues downstream of the convergence point. At this road segment, designers have the freedom to vary between two merger types which are the standard geometric design and a merging taper. In the standard geometric design, which is preferred according to the ROA [21] (Richtlijn voor het Ontwerp van Autosnelwegen), a lane drop is applied on the left lane downstream of the convergence point. As an alternative, a merging taper may be applied which is a merger on which the left through lane on the right roadway is tapered and connected to the right through lane on the left roadway.

PROBLEM DEFINITION

In the ROA [21] it is presumed that a merging taper is unsafe compared to the standard geometric design, and therefore the choice for a merging taper must be well motivated (for example lack of space in longitudinal direction). However, this presumption is not underpinned and therefore it is unclear whether this presumption is correct. The design guidelines for merging tapers are not underpinned either, and therefore it is unclear whether these are correct. As a result, road safety on merging tapers is unclear, and the effect of deviating from the design guidelines on road safety is unclear. However, road safety is one of the most important aspects throughout the design process of Dutch motorways.

This study investigated road safety on merging tapers, for which the following two research questions were formulated:

- *What is the road safety on merging tapers compared to the road safety on the standard geometric design?*
- *How do varying road designs and traffic conditions affect the road safety on merging tapers?*

Road safety is defined as the safety in road traffic, and can be divided into subjective road safety and objective road safety. Subjective road safety is the perception of road safety, which is for example the opinion of road users on road safety. Objective road safety is based on numbers such as the number of accidents per time unit, or performance in terms of driving behaviour.

METHOD

The first step in this study was to find an underpinning for the design guidelines and the presumption that merging tapers are unsafe. In both Dutch and foreign literature, no further explanation about the presumption and design guidelines was found. In further literature study, it was found that the taper-length [23], traffic volume [24] and the percentage of heavy vehicles [25] may influence road safety on merging tapers. Therefore, the factors taper-length, traffic volume on both the left roadway and the right roadway and the percentage of heavy vehicles were further taken into account in this study.

Three methods were used to measure road safety, knowing:

- **Accident analysis** was performed with accident registrations in BRON [22], to measure "objective" road safety. Accident registrations were collected for representative merging tapers and mergers with the standard geometric design in the period between 2010 and 2013.
- A **questionnaire** was conducted to measure subjective road safety of merging tapers compared to the standard geometric design. Besides, socio-demographic data of the participants was collected. This questionnaire was conducted prior to a driving simulator experiment.

- A **driving simulator experiment** was performed to measure driving behaviour using vehicle trajectories. An assessment of road safety was given using surrogate safety measures which were calculated from the vehicle trajectories. Eight merging tapers were present in the experiment with varying taper-length, traffic volume and percentage of heavy vehicles. One standard geometric design was implemented which was designed according to the design guidelines, and an average traffic volume and 20% heavy vehicles were applied. VISSIM has been integrated for simulating the other traffic, which reacted on the participant's driving behaviour. VISSIM collected data of both the participant's vehicle and the other traffic. In addition, a questionnaire was conducted after the experiment to obtain the driving simulator's realism.

RESULTS

From the **accident analysis** it was found that the number of registered accidents between 2010 and 2013 varied between one and fifteen accidents per merging taper. Only three representative mergers with the standard geometric design were found, on which on average 73% more accidents were registered compared to merging tapers. Accidents which were registered on merging tapers were analysed in more detail, and it was found that most accidents occurred during peak hours which indicates that the traffic volume affects the number of accidents and thus road safety. Furthermore it was found that the accident data is of poor quality, as accident registration is mostly incomplete. However, it is assumed that the incomplete accident registration is equally divided over time and the locations, and therefore the data was considered indicative for the purpose of this analysis.

In the driving simulator experiment, a total of 41 participants took part both at TU Delft and Witteveen+Bos office. In the **questionnaire**, 65,9% stated they will feel safer on the standard geometric design, 19,5% stated they will feel safer on a merging taper and the rest stated they will feel equally safe. Therefore, the subjective road safety on merging tapers was considered low compared to the standard geometric design. In the second questionnaire, participants were positive about the realism of the environment in the driving simulator such as guide rails, buildings and trees. However, they were negative about the realism of the vehicle's characteristics and the realism of actions performed by other vehicles. Many participants stated they made driving errors which they would not make in real life. However, it was assumed that the driving simulator is still useful to measure the direction of the effects, but no exact values can be provided that would indicate a threshold for a safe/unsafe road design.

In order to compare the road safety of merging tapers with the standard geometric design based on data obtained in the **driving simulator experiment**, surrogate safety measure's values from all merging tapers were averaged and compared with measurements from the standard geometric design. This was done for the output variables time headway, time to collision, driving speed and number of lane changes. A paired samples t-test was used to determine whether the mean difference between the measurements was statistically significant. The results seem to point in the direction that the road safety on merging tapers could be safer as compared to the standard geometric design. However, none of the mean differences were statistically significant. Therefore, from the driving simulator's results it can not be said whether merging tapers are more or less safe compared to the standard geometric design.

In order to measure the effect of taper-length, traffic volume and percentage of heavy vehicles on the output variables time headway, time to collision, driving speed and number of lane changes, two linear mixed models were estimated based on data which was collected in the driving simulator. It was found that the traffic volume on the right roadway and the percentage of heavy vehicles had a significant negative effect on time to collision values, and thus point at a negative effect on road safety. The taper-length had a significant positive effect on time to collision values, and thus point at a positive effect on road safety. All factors had a significant effect on driving speed. However, the measured driving speed was much lower than the speed limit, and therefore the road safety effect of driving speed is debatable. No significant results were found regarding the number of lane changes. A statistically significant interaction was found between percentage of heavy vehicles and taper-length on time to collision. The estimate indicated that the effect of taper-length on time to collision values was smaller if no heavy vehicles were present. This means that the effect of taper-length on road safety is smaller if no heavy vehicles are present. Furthermore it was found that the most unsafe driving behaviour on merging tapers took place at the end of the tapered lane.

CONCLUSION

From the findings in the first questionnaire it was concluded that the subjective road safety of merging tapers is low compared to the standard geometric design. From the driving simulator results, it can not be concluded whether the driving behaviour on merging tapers is more or less safe compared to the standard geometric design. From the driving simulator results it is concluded that the taper-length has an effect on road safety; the longer the taper-length, the more safe the merging taper. From the accident analysis results and driving simulator results, it is concluded that the traffic volume on the right roadway has an effect on road safety; the higher the traffic volume, the less safe the merging taper. Based on the driving simulator results it is concluded that heavy vehicles have an effect on road safety; the more heavy vehicles, the less safe the merging taper.

RECOMMENDATIONS

It is recommended to get a better insight in the exact road safety on merging tapers, and the effect of deviating from the guidelines on road safety. This study showed that the taper-length, traffic volume on the right roadway and percentage of heavy vehicles have an effect on road safety, because a significant effect of these factors on time to collision were measured. Therefore it is recommended to consider whether the road safety on the existing merging tapers with a deviating design is sufficient. It is recommended to decision makers to be cautious with applying merging tapers instead of the standard geometric design. Merging tapers are not less safe regarding the number of accidents and driving behaviour, but it has shown that the subjective road safety of merging tapers is low. It is recommended to apply a minimum taper-length of 140 m, and use realistic and reliable traffic volume and traffic composition forecasts. Further research on the road safety on merging tapers may be done with accident analysis and a driving simulator experiment. First, improvement of the accident registration's quality is recommended. Better accident data may be very useful for validating driving simulators and investigating the relation between surrogate safety measures and accident data. Accident registration can for example be improved by simplifying the registration process with mobile applications, internet and GPS. Second, it is recommended to perform road safety studies in a driving simulator with better graphics and better vehicle characteristics. The simulator vehicle's behaviour may also be improved, for example by doing further research on how to translate actions in the simulator to actions in the simulated environment. Knowledge on this topic in for example formula 1 should be used in driving simulators which are developed for road safety research purposes. Furthermore it is recommended to do further research on how to analyse data obtained from a driving simulator faster and with a smaller error. The latter may already be partly obtained by using driving simulators with a high computation power. It is possible to collect data from more vehicles at the same time, so that a conflict between two vehicles will not be missed in the data. Furthermore, a higher computation power allows researchers to make the simulation more realistic in terms of graphics and simulation of other traffic.

SAMENVATTING

In het ontwerpproces voorafgaand aan het bouwen of herbouwen van Nederlandse snelwegen hebben ontwerpers de vrijheid om te variëren tussen verschillende ontwerpopties. Dit is onder andere het geval bij samenvoegingen. Een samenvoeging is gedefinieerd als een convergentiepunt van twee rijbanen met dezelfde ontwerpsnelheid, en voor beide rijbanen geldt dat stroomafwaarts van het convergentiepunt minstens één van de rijstroken aanblijft. Voor dit wegsement kan de ontwerper variëren tussen twee types, namelijk het standaard geometrisch ontwerp en de taper-samenvoeging. Op het standaard geometrisch ontwerp, welke de voorkeur heeft volgens de ROA [21] (Richtlijn voor het Ontwerp van Autosnelwegen), is een rijstrookvermindering toegepast aan de linkerzijde van de rijbaan. Als alternatief op dit ontwerp kan een taper-samenvoeging worden toegepast, op welke de linker rijstrook van de rechter rijbaan taps toeloopt en is aangesloten op de rechter rijstrook van de linker rijbaan.

PROBLEEMSTELLING

In de ROA [21] wordt verondersteld data een taper-samenvoeging onveilig is in vergelijking met het standaard geometrisch ontwerp, en daarom moet de keuze voor een taper-samenvoeging goed worden onderbouwd (bijvoorbeeld ruimtegebrek in lengterichting). Echter, de aanname dat een taper-samenvoeging onveilig is, is niet onderbouwd en daarom is het onduidelijk of deze aanname juist is. Daarnaast zijn de ontwerprichtlijnen voor taper-samenvoegingen ook niet wetenschappelijk onderbouwd, en daardoor is het onduidelijk of deze juist zijn. Als een gevolg hiervan is de verkeersveiligheid op taper-samenvoegingen onduidelijk, en het is onduidelijk wat het effect van afwijken van de richtlijnen is op verkeersveiligheid. Echter, de verkeersveiligheid is een van de belangrijkste onderwerpen tijdens het ontwerpproces.

In deze thesis is de verkeersveiligheid op taper-samenvoegingen onderzocht, aan de hand van de volgende twee onderzoeksvragen:

- *Wat is de verkeersveiligheid op taper-samenvoegingen in vergelijking met de verkeersveiligheid op het standaard geometrisch ontwerp?*
- *Hoe beïnvloeden variërende wegontwerpen en verkeersomstandigheden de verkeersveiligheid op taper-samenvoegingen?*

Verkeersveiligheid is gedefinieerd als de veiligheid in het verkeer, en kan worden gesplitst in subjectieve en objectieve verkeersveiligheid. Subjectieve verkeersveiligheid is de perceptie van de weggebruikers op verkeersveiligheid, dus bijvoorbeeld de meningen en ervaringen van weggebruikers. Objectieve verkeersveiligheid is gebaseerd op getallen zoals de hoeveelheid ongevallen per tijdseenheid.

METHODE

De eerste stap in dit onderzoek was het vinden van onderbouwing van de ontwerprichtlijnen en van een onderbouwing voor de veronderstelling dat een taper-samenvoeging onveilig is. In zowel Nederlandse als buitenlandse literatuur is geen verdere uitleg gegeven over deze veronderstelling en ontwerprichtlijnen. Aan de hand van verder literatuuronderzoek kon worden verwacht dat de taper-lengte, verkeersintensiteit en percentage vrachtverkeer invloed heeft op de verkeersveiligheid op taper-samenvoegingen. Maximale waardes voor taper-lengte en verkeersintensiteit komen voor in de richtlijnen, wat deze twee factoren extra interessant maakt om te onderzoeken. Daarom zijn de factoren taper-lengte, verkeersintensiteit op zowel de linker als de rechter rijbaan en het percentage vrachtverkeer verder meegenomen in dit onderzoek.

De volgende methodes om verkeersveiligheid te meten zijn gebruikt in deze studie:

- **Ongevallenanalyse** is uitgevoerd met ongevallendata welke is geregistreerd in BRON [22], om "objectieve" verkeersveiligheid te meten. Ongevallendata is verzameld voor representatieve tapersamenvoegingen en samenvoegingen met het standaard geometrisch ontwerp voor de periode van 2010 tot en met 2013.

- Er is een **enquête** uitgevoerd om subjectieve verkeersveiligheid van taper-samenvoegingen te meten en te vergelijken met het standaard ontwerp. Daarnaast is socio-demografische data van de deelnemers verzameld. Deze enquête is uitgevoerd vóór het rijsimulatorexperiment.

- Een **rijsimulatorexperiment** is uitgevoerd om rijgedrag te meten met behulp van voertuigtrajectoriën. De verkeersveiligheid is bepaald door surrogate safety measures te berekenen vanuit de verzamelde voertuigtrajectoriën. Acht taper-samenvoegingen waren in het experiment verwerkt, met variërende taper-lengte, verkeersintensiteit en percentage vrachtverkeer. Eén standaard ontwerp was geïmplementeerd in het experiment welke was ontworpen volgens de ontwerprichtlijnen, en een gemiddelde verkeersintensiteit en 20% vrachtverkeer was toegepast. Het microscopische simulatieprogramma VISSIM was geïntegreerd in de rijsimulator, welke het overige verkeer simuleerde en de data van alle voertuigen verzamelde. Daarnaast is na het rijsimulatoronderzoek een enquête afgenomen om het realisme van de rijsimulator te onderzoeken.

RESULTATEN

Uit de **ongevallenanalyse** is gebleken dat de hoeveelheid ongevallen tussen 2010 en 2013 varieërt tussen de één en vijftien ongevallen per taper-samenvoeging. Enkel drie representatieve samenvoegingen met het standard geometrisch ontwerp zijn gevonden, waarop gemiddeld 73% meer ongevallen zijn geregistreerd vergeleken met taper-samenvoegingen. Ongevallen die plaatsvonden op taper-samenvoegingen zijn in meer detail geanalyseerd, en het is gebleken dat de meeste ongevallen plaatsvonden tijdens de spits wat aangeeft dat de verkeersintensiteit effect heeft op de hoeveelheid ongevallen en dus verkeersveiligheid. Daarnaast is gebleken dat de ongevallendata van slechte kwaliteit is, omdat de ongevallenregistratie incompleet is. Echter, het is aangenomen dat de onvolledigheid van de ongevallenregistratie gelijk verdeeld is over de tijd en locaties, en daarom is de data bruikbaar voor het doel van deze analyse.

In het rijsimulatorexperiment hebben in totaal 41 deelnemers meegedaan op de TU Delft en het kantoor van Witteveen+Bos in Amsterdam. In de **enquête** verklaarde 65,9% dat zij zich veiliger voelen op het standaard geometrisch ontwerp, 19,5% verklaarde dat zij zich veiliger voelen op een taper-samenvoeging, en de rest voelt zich even veilig op beide ontwerpen. Daarom kan worden gesteld dat de subjectieve verkeersveiligheid op taper-samenvoegingen laag is in vergelijking met het standaard wegontwerp. In de tweede enquête bleek dat de deelnemers positief zijn over het realisme van de gesimuleerde omgeving, zoals bijvoorbeeld de geleiderails. Echter, de deelnemers waren negatief over het realisme van de voertuigkarakteristieken en de manoeuvres van de andere voertuigen. Veel deelnemers gaven aan dat ze manoeuvres maakten die ze in de realiteit niet zouden maken. Dit resultaat is meegenomen in de interpretatie van de resultaten. Echter, het is aangenomen dat de rijsimulator nog steeds geschikt is om de richting van de effecten te onderzoeken, maar exacte getallen die een veilig of onveilig ontwerp aanduiden kunnen niet worden berekend.

Om de verkeersveiligheid van taper-samenvoegingen te vergelijken met dat van het standaard ontwerp met data uit het **rijsimulatorexperiment**, is het gemiddelde van de surrogate safety measures metingen op alle taper-samenvoegingen vergeleken met de metingen op het standaard ontwerp. Dit is gedaan voor time headway, time to collision, rijsnelheid en aantal rijstrookwisselingen. Een paired samples t-test is uitgevoerd om te bepalen of het verschil tussen de gemiddelden statistisch significant is. De resultaten lijken erop te wijzen dat een taper-samenvoeging veiliger is dan het standaard geometrisch ontwerp. Echter, geen van de resultaten zijn significant. Daarom kan er op basis van deze resultaten geen uitspraak worden gedaan over de verkeersveiligheid van taper-samenvoegingen in vergelijking met het standaard geometrisch ontwerp.

Om het effect van de taper-lengte, verkeersintensiteit en percentage vrachtverkeer op de outputvariabelen time headway, time to collision, snelheid en aantal rijstrookwisselingen te meten, zijn linear mixed models geschat. De verkeersintensiteit op de rechter rijbaan en het percentage vrachtverkeer hadden een significant negatief effect op time to collision, en dus wijzen deze effecten op een negatief effect op verkeersveiligheid. Daarnaast had de taper-lengte een significant positief effect op time to collision, dat wijst op een positief effect op verkeersveiligheid. Alle factoren bleken een significant effect op de snelheid te hebben. Echter, de gemeten snelheid was veel lager dan de maximum toegestane snelheid, en daarom kan worden getwijfeld in hoeverre het gemeten snelheidsverschil invloed heeft op de verkeersveiligheid. Er zijn geen significante resultaten gemeten voor het aantal rijstrookwisselingen op taper-samenvoegingen. Tot slot is het gebleken dat het meest onveilige rijgedrag heeft plaatsgevonden ter hoogte van het eind van de getaperde rijstrook.

CONCLUSIE

Op basis van de resultaten uit de eerste enquête is geconcludeerd dat de subjectieve verkeersveiligheid van taper-samenvoegingen laag is in vergelijking met het standaard wegontwerp. Met het rijgedrag uit het rijsimulatorexperiment kon niet worden bepaald of taper-samenvoegingen veiliger of onveiliger zijn in vergelijking met het standaard geometrisch ontwerp. Uit het rijsimulatoronderzoek kan worden geconcludeerd dat de taper-lengte een effect heeft op verkeersveiligheid; hoe langer de taper-lengte, hoe veiliger de taper-samenvoeging. Op basis van de ongevallenanalyse en rijsimulatoronderzoek kan worden geconcludeerd dat de verkeersintensiteit op de rechter rijbaan effect heeft op de verkeersveiligheid; hoe hoger de verkeersintensiteit, hoe onveiliger de taper-samenvoeging. Op basis van de resultaten uit de rijsimulator kan worden geconcludeerd dat vrachtverkeer een invloed heeft op de verkeersveiligheid op taper-samenvoegingen; hoe hoger het percentage vrachtverkeer, hoe onveiliger de taper-samenvoeging.

AANBEVELINGEN

Het is aanbevolen om een beter inzicht te krijgen in de exacte verkeersveiligheid van taper-samenvoegingen, en het effect van afwijken van de ontwerprichtlijnen op verkeersveiligheid. Dit onderzoek heeft aangetoond dat de taper-lengte, verkeersintensiteit op de rechter rijbaan en het percentage vrachtverkeer een effect hebben op verkeersveiligheid, omdat significante effecten op time to collision zijn gemeten. Daarom zou kunnen worden overwogen of de verkeersveiligheid op de bestaande afwijkende tapersamenvoegingen wel voldoende is. Het is aanbevolen om voorzichtig te zijn met het toepassen van tapersamenvoegingen. Tapersamenvoegingen zijn niet minder veilig met betrekking tot ongevallen en rijgedrag, maar de subjectieve veiligheid van tapersamenvoegingen is laag. Het is aanbevolen om een minimale taperlengte van 140 toe te passen, en gebruik te maken van een betrouwbare en realistische voorspelling van verkeersintensiteit en verkeer samenstelling. Verder onderzoek naar de verkeersveiligheid van taper-samenvoegingen kan worden gedaan met ongevallenanalyse en een rijsimulatorexperiment. Daartoe is aanbevolen om de ongevallenregistratie te verbeteren. Betere kwaliteit ongevallendata kan erg nuttig zijn bij het valideren van rijsimulatoren en het onderzoeken van de relatie tussen surrogate safety measures en ongevallendata. Er wordt geadviseerd om het registratieproces van ongevallen te vergemakkelijken met mobiele applicaties, internet en GPS. Daarnaast wordt geadviseerd om verkeersveiligheidstudies in een rijsimulator met betere grafische vormgeving en betere voertuigkarakteristieken. Het gedrag van het rijsimulatorvoertuig kan ook worden verbetere, bijvoorbeeld door verder onderzoek te doen naar hoe handelingen in het voertuig worden omgezet in acties in de rijsimulator. Kennis over dit onderwerp uit bijvoorbeeld de formule 1 zou moeten worden gebruikt in rijsimulators welke gebruikt worden voor verkeersveiligheidonderzoek. Daarnaast wordt aanbevolen om verder onderzoek te doen naar hoe de data uit de rijsimulator sneller en met een kleinere foutmarge kan worden geanalyseerd. Dit laatste kan al gedeeltelijk worden behaald door meer computerkracht te gebruiken. Het is dan mogelijk om data van meer voertuigen tegelijk te verzamelen, zodat een conflict tussen twee voertuigen niet wordt gemist. Verder geeft meer computerkracht de mogelijkheid om de simulatie realistischer te maken wat betreft grafische vormgeving en simulatie van overige voertuigen.

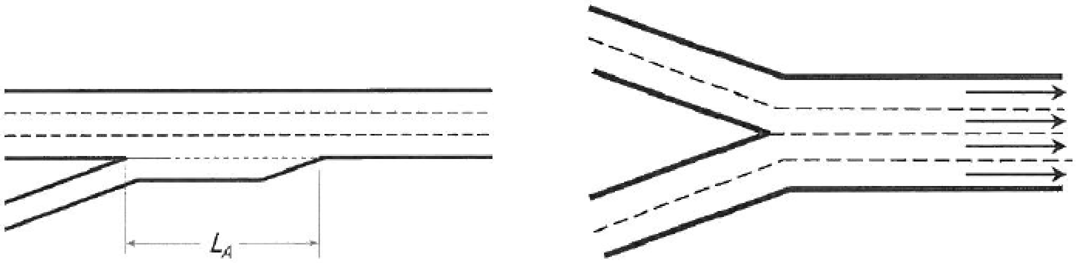
1

INTRODUCTION

1.1. BACKGROUND

When building or rebuilding motorways in the Netherlands, guidelines from the ROA [21] (Richtlijn Ontwerp Autosnelwegen) are used in the designing process. These guidelines give advice on how Dutch motorways should be designed. However, in many cases designers deviate from the prescribed guidelines to accommodate the design to the local conditions. In the final road design, designers have to meet the requirements for traffic flow, road safety, and costs in order to prevent undesirable solutions. Traffic simulation models, road safety audits and clearly specified budgets are used to check whether these requirements are met.

A merger is one of the road segments where road designers may vary. According to the ROA, a merger is defined as follows: “A merger is a convergence point of two roadways with a similar design speed. For both roadways holds: at least one of the lanes continues downstream of the convergence point”. Some similarities exist between mergers and acceleration lanes, but distinctions are made in the guidelines. Schematic geometric designs of both a merger as an acceleration lane are shown in figure 1.1. According to the guidelines, a merger is applied if the design speed of both roadways is similar, and of both roadways at least one lane continues downstream of the convergence point. An acceleration lane is applied at a convergence point if a one-lane roadway is inserted in the main roadway. The inserted roadway does not necessarily continue downstream of the convergence point.



(a) Acceleration lane

(b) Merger

Figure 1.1: Schematic geometric design of an acceleration lane and a merger. [1]

At mergers, from a capacity point of view, downstream of the convergence point often fewer lanes are needed than the sum of lanes upstream of the convergence point. According to the ROA [21], it is in this situation preferred to apply a lane drop on the left lane after the convergence point. A schematic representation of this geometric design can be seen in figure 1.2, and is called “the standard geometric design".

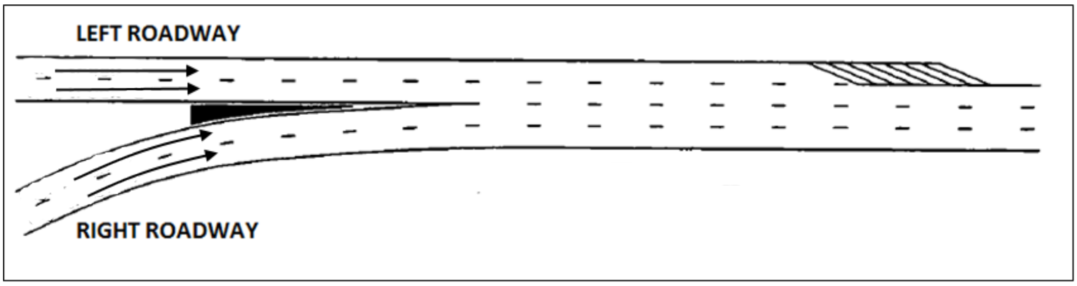


Figure 1.2: Schematic representation of the standard geometric design of a merger. [2]

As an alternative to the standard geometric design of a merger, a merging taper can be applied. Merging tapers are defined as follows: "At a merging taper, the left through lane on the right roadway is tapered and connected to the right through lane on the left roadway". Examples of merging tapers can be seen in figure 1.3. According to the most recent design guidelines (ROA [21]), merging tapers have a negative influence on road safety. Therefore, the application of a merging taper instead of the standard geometric design must be clearly motivated.

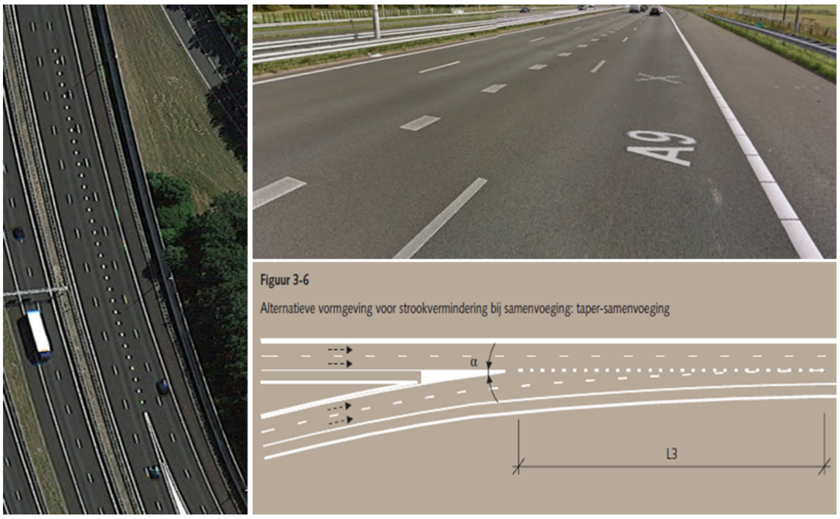


Figure 1.3: Different visualizations of merging tapers. [3] [4]

According to the ROA [21], one of the motivations to apply a merging taper instead of the standard geometric design, is a lack of space in longitudinal direction. The example below shows that 500 meters in longitudinal direction can be saved, assuming a design speed of 120 km/h. The second motivation according to the ROA [21] is the decrease of traffic flow disruption. Assuming heavy vehicles approaching on the left roadway are driving mainly on the rightmost lane, downstream of the convergence point only one lane change is necessary instead of two lane changes to maintain driving on the right most lane.

The case is as follows: Assuming a design speed of 120 km/h, two two-lane roadways merge and downstream of the convergence point only 3 lanes are needed from a capacity point of view. Two options are considered, which are designed according to the guidelines of the ROA [21]:

1. **Standard geometric design:** Downstream of the convergence point, a lane drop is applied on the left lane of the left roadway. Due to turbulence a minimum length (turbulence length) must be applied upstream and downstream of discontinuities, which are the merger and the lane drop. The turbulence length is measured from the mergers' point of the gore and the end of the lane drop. After combining the two turbulence lengths, a distance of 750 meters between the convergence point and lane drop is obtained.
2. **Merging taper:** The left lane of the right roadway is tapered connected to the right lane of the left roadway. The tapered lane starts at the merger's point of the gore, and has a length of 250 meters. This results in a distance of 250 meters between the convergence point and lane drop.

1.2. PROBLEM DEFINITION

Designing or redesigning a new motorway is a trade-off between road safety, capacity and costs. This also holds when designing or redesigning a merger where a lane drop is applied downstream of the convergence point. According to the ROA [21] it is standard to apply the standard geometric design, but if well motivated, a merging taper can be applied as an alternative. However, according to the ROA [21], it is presumed that merging tapers have a negative influence on road safety.

However, the underpinning for this presumption in the guidelines is very limited. The presumption is stated without any further explanation and scientific basis. Therefore it is unclear whether this presumption is correct, and thus whether merging tapers are actually less safe than the standard geometric design. Assuming the presumption is correct, it is unclear how much less safe a merging taper is compared to the standard geometric design.

The merging taper's design guidelines given in the ROA [21] are neither underpinned, and therefore it is unclear whether the values' guidelines are correct (and thus provide a safe road design). As a result of this, it is unclear what the effect of a deviating road design and traffic conditions is on road safety at merging tapers. Consequently it is unclear under which conditions (traffic conditions and road design) a merging taper is less safe than the standard geometric design.

1.3. RESEARCH QUESTIONS, RESEARCH OBJECTIVE AND APPROACH

Road safety is an important issue when designing, redesigning and maintaining motorways. Therefore, following the problem defined in section 1.2, the following two main research questions are formulated:

1. *What is the road safety on merging tapers compared to the road safety on the standard geometric design of a merger?*
2. *How do varying road designs and traffic conditions affect the road safety on merging tapers?*

The main research objective pursued in order to answer the research questions is:

"to compare road safety on the standard geometric design with road safety on merging tapers in different road designs and under different traffic conditions."

Road safety can be defined as the safety in road traffic. Two types of road safety exist, which are subjective road safety and objective road safety. Subjective road safety is the perception of road safety, and thus an opinion of road users on road safety. This type of road safety is difficult to quantify, since it differs for each person. Objective road safety is based on numbers, and is therefore easier to quantify. This type of road safety is often used to express road safety, such as the number of accidents per year on a road section.

Driving behaviour is the combination of all behavioural aspects of a road user, and consists of longitudinal and lateral driving behaviour. Longitudinal driving behaviour consists for example of speed, acceleration/deceleration and car-following. Lateral driving behaviour consists for example of lane changing and the road users' lateral position on the road. The driving behaviour of road users is among others based on expectations which are shaped by driving experiences in the past. Furthermore, the driving behaviour is influenced by several conditions such as road design, traffic volume, traffic composition and weather conditions. Driving behaviour influences road safety, since for example speeding and tailgating are important contributing factors to accidents.

Accident analysis was performed to measure "objective" road safety, by analysing registered accidents on representative locations. In order to give an assessment on subjective road safety, a questionnaire was conducted in which road users can state their perception of road safety. A driving simulator experiment was performed to measure driving behaviour using vehicle trajectories. From the driving behaviour, surrogate safety measures were calculated from which road safety is interpreted.

1.4. SCOPE

This study focusses on mergers which are located on Dutch motorways and which are designed following the Dutch design guidelines.

Mergers are solely taken into account if the driving behaviour at the merger is not influenced by external effects caused by other discontinuities than the merger itself. No discontinuities such as on-ramps and off-ramps may be located within the margin of the turbulence length upstream and downstream of the merger. The ROA [21] states that the turbulence length upstream of the point of the gore is 150 m, and downstream of the taper-point the turbulence length is 375 m assuming a design speed of 120 km/h. In addition, merging tapers on weaving sections are taken into account in this study.

A first analysis shows that the configuration of Dutch mergers is commonly 2+2 lanes. Therefore, solely 2+2 lanes configured mergers are taken into account in this study.

1.5. REPORT OUTLINE

In this section, the outline of this report is given.

Chapter 2 discusses relevant background for this study. First, more information is gathered on the stated presumption and Dutch and foreign design guidelines. Then several factors are discussed which influence road safety at mergers. Finally, methods are discussed which can be used to measure objective and subjective road safety.

Chapter 3 discusses the research gap, research questions and corresponding hypotheses.

Chapter 4 explains which data is needed to answer the research questions stated in chapter 3, and which methods are used in order to obtain this data. It is also explained which statistical analysis are used in order to answer the research questions.

Chapter 5 discusses the results obtained from the data analysis, for each separate research method.

Chapter 6 presents the conclusions of this study. Also the limitations of the research methods are discussed, as well as recommended further research on this topic.

2

BACKGROUND

2.1. DESIGN GUIDELINES FOR MERGERS

The previous chapter made clear that the underpinning of the design guidelines for merging tapers is very limited. Besides, the presumption that a merging taper is less safe than the standard geometric design is not underpinned. Before doing further research on road safety at merging tapers, it is important to get familiar with the relevant design guidelines and possibly find an underpinning for the presumption. Next to Dutch guidelines, foreign guidelines are studied to find more background about designing similar geometric designs.

2.1.1. DUTCH GUIDELINES

Motorways in the Netherlands are designed according to design guidelines from the ROA [21]. This paragraph explains the geometric design of merging tapers in more depth, based on these design guidelines.

As discussed in section 1.1, different options are available when designing a merger. Either the standard geometric design or a merging taper may be chosen. A schematic representation of a merging taper can be seen in figure 2.1. The arrows indicate the driving direction of the vehicles. The left lane of the right roadway is tapered connected to the right lane of the left roadway. The taper-length is the distance between the point of the gore at the convergence and the taper-point, and depends on the design speed of the merger. The most recent taper-length guidelines are prescribed in the ROA [21], and can be seen in table 2.1.

Figure 2.1: Schematic representation of the geometric design of a merging taper. [4]

Table 2.1: Taper-length prescribed in the ROA [21], depending on the design speed.

Design speed [km/h]	Taper-length [m]
120	250
90	190
70	150

In addition to the guideline on taper-length, a maximum traffic volume is prescribed. The NOA [4], the predecessor of the ROA [21], states that the V/C-ratio (Volume/Capacity-ratio) on the left roadway should not exceed 0,8. This says that the predicted traffic volume should not be higher than 0,8 multiplied by the capacity of the road. The CIA (Capaciteitswaarden Infrastructuur Autosnelwegen) [26] defines the capacity of a road as: "the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway conditions, traffic conditions and control conditions. ". Assuming a 2-lane roadway and a V/C-ratio of 0,8, the predicted traffic volume on the left roadway should not exceed 3956 PCU per hour. The V/C-ratio has been lowered to 0,7 in the ROA [21]. This results in a maximum predicted traffic volume of 3462 PCU per hour, and holds for both roadways. However, the reason for lowering this ratio is not stated in the guidelines.

In addition to the guidelines stated above, the following requirements for the application of merging tapers are given:

- A merging taper may only be applied on convergence points where (at least) the right roadway is not a main roadway, because of the inferior character of this roadway.
- There should exist a clear motivation to deviate from the standard geometric design, for example lack of space in longitudinal direction.
- The left roadway has at least two lanes.
- Until 150 meters downstream the taper-point, the road environment may not demand special attention. This holds there are no road signals, and there is a spacious alignment.
- Over any length, the right roadway should not run parallel to the left roadway. In other words, the two roadways must always be under a small angle.
- Alongside the tapered lane, on the left side a blocked line is necessary. In this way it is clear to the road users that a merging taper is appearing.
- When the merging taper is located in a curve, the radius must be minimum 4000 meters.

For the guidelines and requirements stated in this paragraph, no underpinning is found in the NOA [4] and ROA [21]. In order to gain more information on the guidelines' underpinning, two experts in the field were interviewed [27] [28]. From these interviews no scientific underpinning was obtained for the presumption and guidelines. It became clear that lowering the V/C-ratio from 0,8 to 0,7 has been done, so that in the designing process more attention will be paid to traffic flow. However, the interviews made clear that the V/C-ratio is never tested precisely, but the traffic flow is examined using traffic simulation software. As a result, it is still unclear whether the guidelines' values provide a safe road design and how deviating from these guidelines affects road safety.

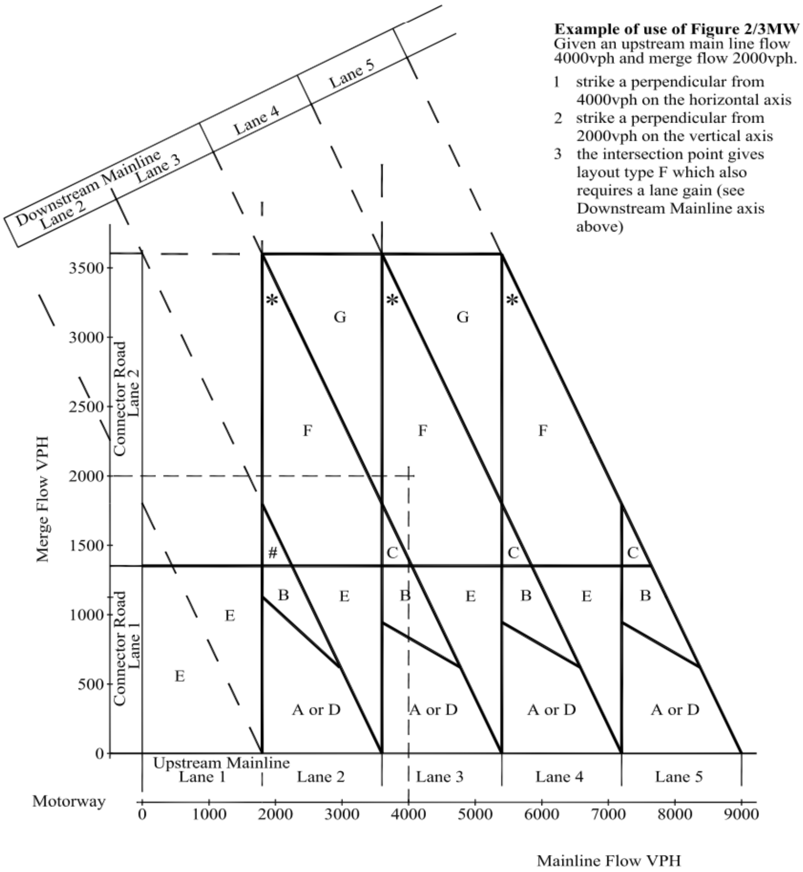
2.1.2. FOREIGN GUIDELINES

The previous paragraph has shown that no background and underpinning is given in Dutch design guidelines. This paragraph reviews literature about foreign guidelines of similar geometric designs. It is expected that foreign guidelines in general deviate from Dutch guidelines, since driving behaviour and design standards are different abroad. However, background and underpinnings given in foreign guidelines might help understanding the Dutch design guidelines and their underpinning.

BRITISH GUIDELINES

The British Standards for Highways [5] give guidelines for the design of mergers. A diagram (figure 2.2) is designed in order to determine which merger design is preferred in each situation. Each letter in the diagram represents a specific geometric design. The traffic volume determines which geometric design is preferred, and can be found by looking up the predicted traffic volumes on the axis of the diagram. On the horizontal axis, the mainline flow must be found which is similar to the traffic volume on the left roadway on Dutch motorways. On the vertical axis, the merge flow must be found which is similar to the traffic volume on the right roadway on Dutch motorways. When drawing a perpendicular from these points, the intersection point gives the preferred merger design.

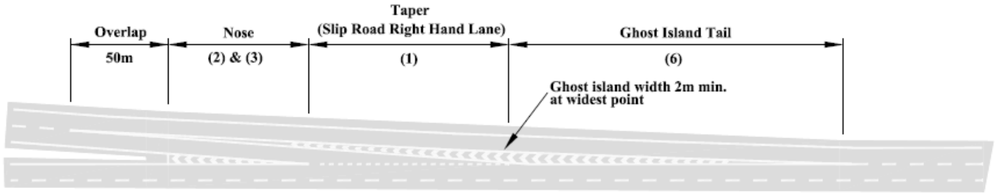
The geometric design of merger "F" has the most similarities with the Dutch merging taper. In the diagram, it can be seen that the maximum traffic flow on a roadway depends on the traffic flow on the other roadway. Assuming a 2+2 lane configuration and a high mainline flow of maximum 4140 PCU (3600 vehicles per hour, assuming 15% trucks), the merge flow may then be maximum 2070 PCU. This is respectively equal to a V/C-ratio of 0,84 and 0,42. Assuming a low mainline flow of 2300 PCU (V/C-ratio of 0,47), the merge flow may be maximum 4140 PCU (V/C-ratio of 0,84). This calculation shows that the maximum V/C-ratio on one roadway may be high compared to Dutch guidelines (V/C-ratio = 0,7), but the condition holds that the other roadway has a low V/C-ratio. When taking into account the Dutch maximum value for one roadway, the maximum V/C-ratio on the other roadway may be maximum 0,51. It can be concluded that in British guidelines, the V/C-ratio for one roadway may be higher. However, the Dutch maximum V/C-ratio which may be applied to for both roadways is not allowed according to the British guidelines.


Example of use of Figure 2/3MW
Given an upstream main line flow 4000vph and merge flow 2000vph.

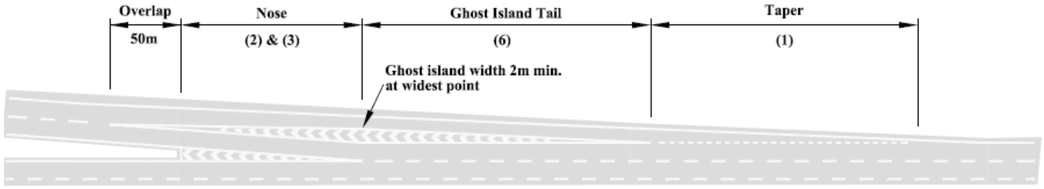
1 strike a perpendicular from 4000vph on the horizontal axis
2 strike a perpendicular from 2000vph on the vertical axis
3 the intersection point gives layout type F which also requires a lane gain (see Downstream Mainline axis above)

Figure 2.2: The Motorway Merging Diagram, which is used to determine the preferred geometric merger design on British motorways. [5]

The schematic geometric design of merger "F" contains two options which can be seen in figure 2.3, and is called a "taper merge". Since it is a British design, lanes are inserted on the left side of the roadway instead of the right side of the roadway. The left roadway is named the "merge roadway", and the right roadway is named the "mainline roadway". If at a merger one lane less is required downstream of the convergence point, a taper merge is always applied. The merge roadway is split upstream of the convergence point. Then there are two options which can be applied to merger "F". In the preferred option, the right lane of the merge roadway is tapered connected to the mainline roadway, and the left lane is added to the mainline roadway as an additional lane. As an alternative, the right lane of the merge roadway is added as an additional lane and the left lane is tapered connected to the mainline roadway. The taper-length for both options is 205 m for rural motorways (maximum speed 70 mp/h (113 km/h)), which is 45 m shorter than the Dutch 120 km/h motorways.



F - Lane Gain with Ghost Island Merge (OPTION 1 - PREFERRED)



F - Lane Gain with Ghost Island Merge (OPTION 2 - ALTERNATIVE - See Paragraph 2.30)

Figure 2.3: Schematic geometric design of a British merger which is similar to the Dutch merging taper. [5]

US GUIDELINES

In the American road design guidelines (Highway Design Manual [29]), no information is found about merging tapers. In the Highway Capacity Manual [1], a basic design of a one-lane tapered acceleration lanes is given without further underpinned guidelines. The Roadway Design Guide of Colorado [6] provides a schematic design of a merging taper variant at an on-ramp, and is shown in figure 2.4. The design of the merging taper is determined by L_a and L_g, which are respectively the acceleration length and the required gap acceptance length. The greatest distance of the two is leading for the geometric design. L_g should be at least 90 to 150 meters, depending on the width of the gore. The total taper-length depends on the angle between both roadways. The angle is similar to the angle which is adopted for Dutch merging tapers design with a taper-length of 250 m. However, the Roadway Design Guide of Colorado [6] states that a lane drop downstream of the convergence point is preferred above the geometric design in figure 2.4. It is unclear under which conditions a tapered design may be chosen, and what could be a motivation to choose for a tapered design.

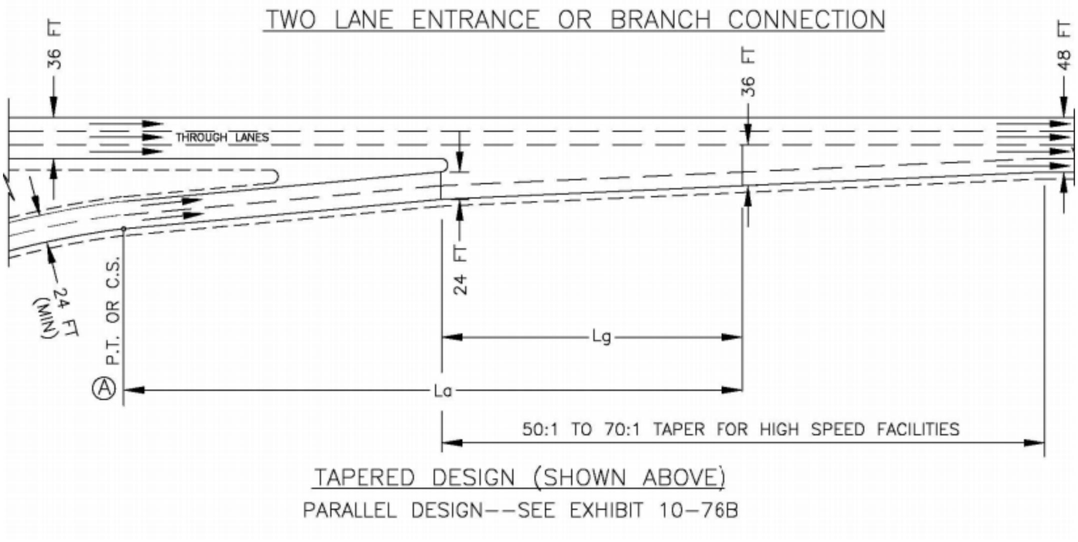


Figure 2.4: Schematic geometric design of a US merger variant at an on-ramp, which is similar to the Dutch merging taper. [6]

German guidelines

A geometric design similar to the Dutch merging taper was applied as an acceleration lane on German motorways. From e-mail contact with the German Federal Highway Research Institute [7] (BASt), a schematic geometric design is obtained which can be seen in figure 2.5. Solely requirements on sight are given, but nothing is given about traffic flows or taper-length. Merging tapers in Germany are no longer applied since 1976 due to higher accidents rates compared to a parallel construction which is conventional on Dutch motorways.

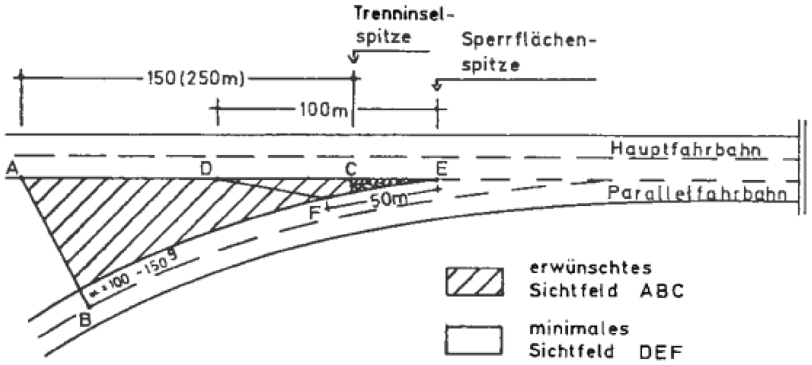


Figure 2.5: Schematic geometric design of a German acceleration lane which is similar to the Dutch merging taper. [7]

2.2. FACTORS INFLUENCING ROAD SAFETY AT MERGERS

The previous section made clear that the literature on design guidelines does not clarify the underpinning of the merging tapers' guidelines, as well as the presumption that merging tapers are unsafe. This section approaches the topic from another point of view. It is discussed what road safety is in general, and how this is affected by certain factors.

Many studies explain specific aspects of driving behaviour which influence road safety. Driving behaviour is built up from different behavioural aspects of the road user, which includes for example speed, acceleration, deceleration, lane changing behaviour and car following behaviour. For example driving behaviour such as speeding is a major contributing factor to a relative high accident rate and injuries [30]. Driving behaviour and thus the road safety may be influenced by many factors such as the road design, traffic conditions and other external effects. In order to get a better insight in how certain factors influence driving behaviour on mergers, a literature review on these factors has been performed in this section.

2.2.1. ROAD SAFETY IN GENERAL

Road safety has been a large topic in Dutch society since approximately 1970. Every year the goal is to reduce the amount of fatalities and injuries in road traffic. After an increase in the number of fatalities in the Netherlands during the 50's and 60's, the number of fatalities shows a decreasing trend since 1973 [**?**]. In 2014, 570 road users died in traffic in the Netherlands which is the same number as in 2013. However, the number of fatalities in 2015 increased to 621 fatalities of which 12,7% died at a motorway [31]. Until 1996, fatalities in road traffic are registered in police reports. Thereafter, fatalities are registered by the CBS in collaboration with the department of Infrastructure and Environment.

Road safety can be defined as the safety in road traffic. Two types of road safety exist, which are subjective road safety and objective road safety. According to the SWOV [32], subjective road safety refers to: "the personal feelings of being unsafe in traffic experienced by people, or, more generally, to the anxiety regarding hazardous traffic situations for themselves and/or others". Subjective road safety is difficult to quantify, since it differs for each person. Objective road safety is based on numbers, and is therefore easier to quantify. This type of road safety is often used to express road safety, and may for example be the number of accidents per year on a road section. SWOV [32] concludes there is mostly a weak link between objective and subjective road safety. This may be the result of road users being extra careful in situations which they consider to be unsafe and adapt their driving behaviour in such a way that it becomes safer from an objective point of view. Another reason could be that road users avoid subjectively hazardous situations by for example choosing a different route.

The probability for a road user to be involved in an accident, is among others a function of the exposure to risk. Exposure is generally defined as the amount of kilometres travelled, either by vehicle or foot [33]. Once the amount of kilometres travelled, the activity and the mode are known, the associated risk can be calculated. Wegman, Aarts and Bax [34] state that for example keeping too short headway distances, driving too fast, driving under adverse visibility conditions etc. increases the exposure to risk. Exposure to risk depends on many factors, which may partly be influenced by the road user itself. Some factors can not be influenced by the road user, for example the traffic volume. Relative high traffic volume increases the exposure to risk, since the mean headway distance decreases if the number of vehicles increases.

SWOV [34] formulated five sustainable safety principles in order to achieve sustainable safe road traffic. The most important features of sustainable safe road traffic are that latent errors in the traffic system are, as far as possible, prevented and that road safety depends as little as possible on individual road user decisions. Latent errors in the system are gaps in the system that result in human errors or traffic violations causing accidents. The complete road environment, including merging tapers, should satisfy the principles of the SWOV [34]. The five sustainable safety principles are the following:

- **Functionality** of roads: Monofunctionality of roads as either through roads, distributor roads, or access roads, in a hierarchically structured road network.
- **Homogeneity** of mass and/or speed and direction: Equality in speed, direction, and mass at medium and high speeds.
- **Predictability** of road course and road user behaviour by a recognizable road design: Road environment and road user behaviour that support road user expectations through consistency and continuity in road design.
- **Forgivingness** of the environment and of road users: Injury limitation through a forgiving road environment and anticipation of road user behaviour.
- **State awareness** of the road user: Ability to assess one's task capability to handle the driving task.

2.2.2. TAPER/MERGING-LENGTH

The first factor which might influence driving behaviour and thus road safety on merging tapers, is the taper-length. Since not much literature on specifically taper-length is available, also literature on merging in general is discussed. One could argue that a relative short merging length may result in smaller accepted gaps and more abrupt movements, since there is less space and thus less time available to change lane. As a result, the number of suitable gaps is less and road users might accept a gap because they have no other choice. This argumentation is found back in the study of Chu [35], which concludes that the remaining distance at an acceleration lane influences the merging behaviour of drivers. If the remaining distance is short, the merging vehicle tends to accept the gap relative directly. If the remaining distance is relatively long, the merging vehicle is likely to continue chasing the leading vehicle on the through lane, until the gap is perceived acceptable. Since the acceleration lane length and the remaining distance are positively correlated, the acceleration lane has effect on the driving behaviour [35]. Although this study is performed on urban expressways in Japan, it is assumed that a similar correlation is present on Dutch motorways.

Wang [23] concludes that the probability of merging failures on acceleration lanes is relative small if the acceleration length is relative long. A merging failure occurs if a road user did not find an acceptable gap before the end of the acceleration lane. Wang [23] also found that more vehicles accept the following gap if the acceleration length is relative long. A following gap is defined as the first gap upstream of the available gap when a road user arrives at the acceleration lane. This means that road users on relative long acceleration lanes have relative often multiple gaps to choose from instead of one.

The geometric design of existing merging taper locations on Dutch motorways is analysed. It is found that more than half of the merging tapers is not designed according to the design guidelines of the ROA [21], since the taper-length is too short on these locations. It is unclear what the effect of this deviation is on road safety because the underpinning of the design guidelines is very limited. However, from literature discussed in this paragraph it may be expected that a too short taper-length will negatively affect road safety.

2.2.3. TRAFFIC VOLUME

Based on many studies, Elvik [24] concludes that a relative high traffic volume is usually positive correlated with the number of accidents. However, the number of accidents is not linearly related to traffic volume: the percentage increase of the number of accidents is less than the percentage increase of traffic volume [24]. This may be the result of road users paying more attention if the the traffic volume is relative high compared to when the traffic volume is relative low.

It is expected that the amount of traffic affects road safety at merging tapers. If the traffic volume is relative high, relative many vehicles are present in a specific road section. The more vehicles are present in a specific road section, the closer the drive from each other. If vehicles drive relative close to each other, little time is available to react on evasive actions such as decelerating, which may result in relative unsafe situations.

At merging tapers, vehicles approaching on the tapered lane must change lane to an adjacent lane. If the traffic volume is relative high, relative much space is blocked by vehicles on the adjacent lanes. As a result, on average smaller gaps may be accepted which has a negative effect on road safety. With this line of reasoning one could expect that a relative high traffic volume has a negative effect on road safety. This expectation is underscored by the V/C-ratio which is mentioned in the design guidelines [21]. Although the underpinning of this guideline is very limited, it may be that the maximum V/C-ratio is mentioned for road safety purposes.

2.2.4. PERCENTAGE OF HEAVY VEHICLES

Heavy vehicles are vehicles which are substantially larger and heavier than regular passenger vehicles. On Dutch motorways, the maximum length of a heavy vehicle is 18,75 meter [36]. Exception on this are "long heavy vehicles", which length is maximum 25,25 meters. Such vehicles are not permitted on Dutch roads before an exemption is accepted, and the driver has completed a special driving exam [37]. From common sense it can be concluded that heavy vehicles have much lower acceleration and deceleration rates than passenger vehicles. Harwood [25] states that due to the size and weight of heavy vehicles, the manoeuvrability is much less than passenger vehicles. Therefore it can be assumed that heavy vehicles need more time for some manoeuvres, for example for lane changing.

Heavy vehicles on Dutch motorways mainly drive on the rightmost lane because their speed is relative low. This could lead to unsafe situations on merging tapers. Road users on the tapered lane must change lane either to the left lane or the right lane. Since the right roadway always contains two lanes, vehicles on the tapered lane always have to merge to a lane with relative high percentage heavy vehicles. Heavy vehicles are relative long vehicles, and therefore relative much space is blocked for vehicles which drive in the tapered lane and want to change lane to an adjacent lane. Since relative much space is blocked by heavy vehicles, the amount of available gaps may be smaller. As a result, road users have less choice and may accept a relative small gap. Therefore, it is expected that the percentage of heavy vehicles negatively affects road safety at merging tapers.

2.2.5. SPEED

Speed can be divided in two different types, namely the absolute speed and the speed variation. Aarts and Van Schagen [30] conclude that the exact relationship between absolute speed and accidents depends on many factors. However, in general the relationship is very clear; a higher absolute speed increases the accident-probability. This has two main reasons. First, the braking distance becomes longer if the absolute speed increases. Second, road users' capabilities to process information is limited. During road users' information processing, more distance is covered during a certain timespan if the absolute speed is higher. The SWOV [8] concludes that a speed-increase at a higher absolute speed has relative much influence on accident-probability, compared to the same speed-increase at a relative low absolute speed. The relation between absolute speed and the accident-probability is shown in figure 2.6. A similar relationship is found in the reviewing paper of Aarts and Van Schagen [30], in which several self-report studies are cited. Besides, Elvik [24] found a relation between the absolute speed and the accident rate.

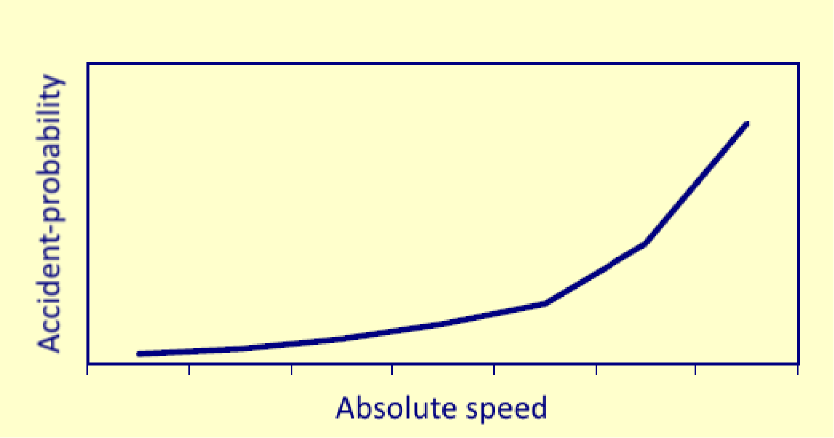
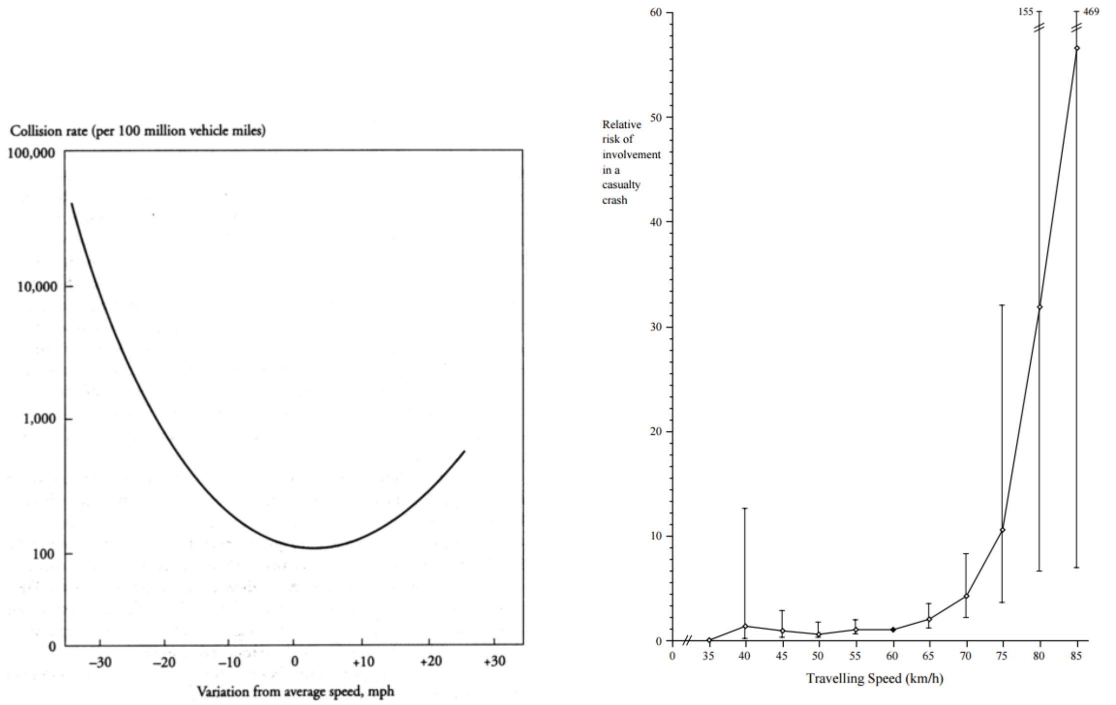


Figure 2.6: Relation between absolute speed and accident-probability. [8]

Speed variation causes speed differences between vehicles. Solomon [38] obtained speed variations by comparing the estimated speed of 10000 case vehicles involved in accidents with the measured speed of 29000 control vehicles. The estimated speeds were based on notes in accident reports, and the measured speeds were measured alongside the road during different moments of the day. He calculated the accident rate for each speed variation, which resulted in the U-shaped Solomon-curve which can be seen in figure 2.7. The Solomon-curve shows that the accident rate is relative high if the speed variation is relative high.

Although similar U-curves are also found in other studies, some weak points can be mentioned. The used speed estimates are inaccurate, and the matches between vehicles' characteristics is lacking. More recent studies found an increased risk for vehicles moving faster than the average speed, but not for vehicles moving slower than the average speed. This is for example concluded by Kloeden [39], who studied accident-probability for 60 km/h speed limit zones. He concluded that each 5 km/h increase in free travelling speed above 60 km/h doubles the risk of involvement in an accident (see figure 2.7). Both the old and the more recent studies conclude that a relative high speed variation increases the accident risk [30]. Based on the literature discussed above it can be concluded that absolute driven speed and speed variation affects road safety on merging tapers.



(a) Solomon-curve: Driving at lower or higher speed than the average speed increases the accident rate [38].

(b) Kloeden-curve: Driving at higher speed than the average speed increases the relative risk of involvement in an accident [39].

Figure 2.7: Relationship between speed variation of individual vehicles and accident rate.

2.2.6. DRIVERS’ CHARACTERISTICS

Road users’ characteristics are an important factor which affects road safety. For example, some driver groups may behave more aggressive and take more risk than other groups. This may lead to a higher number of accidents in these specific driver groups. For example young and novice drivers are relative often killed in accidents [34]. Wegman et al. [34] concludes that causes of this high number of fatalities are classified in three categories: age-specific characteristics, lack of experience and exposure to dangerous conditions.

Examples of age-specific characteristics for young drivers are the influence of friends and groups, exciting events, desire for adventure and experiment and the overestimation of one’s own capacities [34]. Besides, young drivers are inexperienced in their new role in a vehicle. When road users become more experienced they are more capable to indicate dangerous situations, and are able to react on that. The exposure to dangerous situations is mainly influenced by the transport mode which is used. The way in which they are used also influences the level of risk. For example, young drivers drive relative often during night and with influences of passengers, which increases the exposure to danger [34]. Based on the literature discussed above, it can be concluded that drivers’ characteristics affect road safety at merging tapers.

2.2.7. WEATHER CONDITIONS

Weather conditions in the Netherlands vary much between seasons, in seasons itself or even on the same day. A low standing sun, rainfall, wind and snow are examples of weather conditions which influence the driving behaviour. SWOV [40] presents an overview of the effect of several weather conditions on road safety. It is concluded that the accident-risk during rainfall is about twice as high as the accident-risk in dry periods. The accident-risk during fog, snow and hard wind is probably even larger. However, there are four times more accidents during rainfall than during fog, snow and hard wind, simply because it rains more often. Weather conditions are taken into account in the design guidelines of the NOA [4] and ROA [21], so that road safety is of a certain level during bad weather conditions. From the literature discussed above, it can be concluded that certain weather conditions have a negative effect on road safety at merging tapers.

2.3. METHODS TO MEASURE ROAD SAFETY

The literature study on both Dutch and foreign design guidelines in section 2.1 did not explain the underpinning of the merging taper's design guidelines. Section 2.2 discussed the definition of road safety and discussed how traffic conditions and road design affects road safety at mergers. From these two sections it can not be said whether merging tapers are less safe than the standard geometric design, and what is the effect of deviating merging taper designs on road safety.

In order to determine road safety on merging tapers, several research methods may be used. This section discusses some of the methods which may be used to measure road safety.

2.3.1. ACCIDENT ANALYSIS

A conventional method to measure road safety at a specific location is analysing accidents which occurred in the past on that location. The number of accidents and accident severity indicate road safety at the location, because on average accidents will occur more often on locations which are relative unsafe. Archer [18] states that accident data is useful for the identification of specific safety problems, but it is regarded as a re-active approach implying that a significant number of accidents must be recorded before a road safety problem is identified. Besides, the quality and availability of accident data is not always guaranteed. Accidents are not registered consequently, and when registered, the content of the registration is often not detailed enough for research purposes. Ismail [41] states that the content of an accident registration is mainly subjective and biased toward highly damaging collisions, while non-injurious collisions may go unreported. Young [42] summarized many papers, and concluded there is lack of data, the data is collected slow and the data is difficult to use for observing accident processes.

Besides, critical conflicts between two vehicles are not registered if no accident has occurred. For example if two vehicles drive very close to each other as a result of heavy decelerating, no conflict is registered. As a result, an unsafe location may exist without accidents being registered on that location. Also subjective road safety is not taken into account when analysing accident data. Road users may perceive a location as unsafe, but this can not be measured using accident data.

2.3.2. SURROGATE SAFETY MEASURES

A more pro-active method to measure road safety is determining surrogate safety measures. Surrogate safety measures (SSM) are measured from driving behaviour, and may be used in order to measure road safety. The main advantage of SSM is that they occur more often than accidents and therefore this method requires relative short periods of observation [18]. Examples of SSM are *time to collision* and *time headway*. Several other SSM are discussed later in this section, but first the theory underlying SSM is discussed. It is also explained how data can be obtained from which SSM may be calculated.

THEORY UNDERLYING SURROGATE SAFETY MEASURES

Tarko [43] states that surrogate measures are commonly used in the medical science. The meaningful outcome of a medical treatment is quality of life after the treatment. Since this outcome can not be measured during the treatment, surrogate outcomes are necessary to evaluate the treatment beforehand. In road safety, the meaningful outcome is the reduction or even elimination of accidents [43]. Tarko [43] states that a surrogate measure should satisfy two conditions in order to be useful for road safety applications, knowing:

1. A surrogate measure should be based on an observable non-accident event that is physically related in a predictable and reliable way to accidents.
2. There exists a practical method for converting the non-accident events into a corresponding accident frequency and/or severity.

SSM in road safety studies can be calculated from emperical vehicle trajectory data. Different SSM can be used to indicate the conflict-severity between a pair of vehicles. By calculating SSM under varying traffic conditions and road designs, the effect of these varying factors may be assessed. The same method may used in order to compare the road safety of two locations. The theory underlying surrogate safety measures and their relation with conflict-severity are explained in more depth below.

SSM are initially part of a procedure named the *Traffic Conflict Technique(TCT)*. With this procedure, evasive actions can be observed or qualified as a clue to deduce critical situations [15]. The TCT principle was essentially developed to test whether GM (General Motors) cars performed more safe compared to cars of other manufacturers [15]. The procedure is systematically observing evasive actions such as sudden lane-changing or hard braking as an indication of critical situations. More studies followed, and a traffic conflict got a unified definition by Amundsen and Hydén [9]: "A traffic conflict is an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged". The definition of TCT indicates that conflicts must precede accidents but have a lower level of danger. If an evasive action is successfully taken a primary traffic conflict occurs, otherwise a collision occurs [15]. The conflict-collision process suggests a hierarchical continuum representation between conflicts and collisions. Some models are used to describe this representation and schematic representations of these can be seen in figure 2.8.

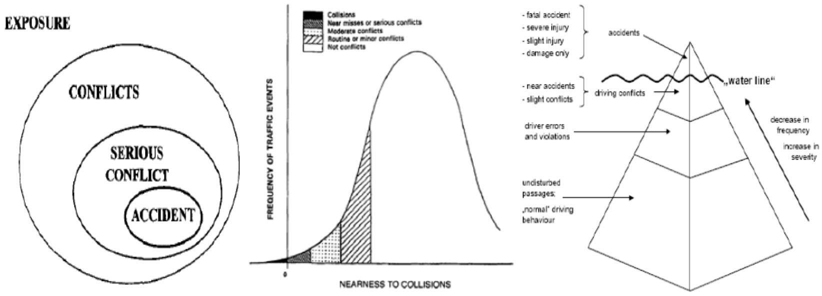


Figure 2.8: Different ways to show the hierarchy between conflicts and accidents: left-hand figure originally from Amundsen and Hydén [9], middle figure originally from Glauz [10], right-hand figure from Hydén. [11]

The left-hand illustration in figure 2.8 is originally from Amundsen and Hydén [9]. Three circles are drawn in a space in which road users are exposed to risk. A part of the exposure leads to conflicts which are illustrated by the outside circle. A part of the conflicts can be defined as serious conflicts, and a small part of the serious conflicts result in an accident. Glauz [10] designed the middle illustration in which a normal distribution is drawn. The vertical axes indicates the frequency of events, and the horizontal axis indicates the nearness to collision. The white surface under the normal distribution indicates exposure to risk. The most right-hand coloured bar indicates minor conflicts. It can be seen that conflicts near to a collision occur less frequently than minor conflicts. If the nearness to collision is equal to zero or smaller than zero, an accident occurs which is illustrated in the surface left of the vertical axis. Hydén [11] drawn the pyramid in the right-hand illustration, in which a similar distribution of conflicts is given. High-severity conflicts are placed on top of the pyramid, as undisturbed traffic is placed at the bottom of the pyramid. The surface of horizontal slices of the pyramid indicate the conflict's frequency for each conflict severity. For example, at the top of the pyramid accidents are placed. Taking a horizontal slice at that location, the surface of that slice is relative small which indicates a relative low frequency. In essence, the three illustrations in figure 2.8 give a similar explanation about the conflict-collision hierarchy.

Svensson [12] improved the right-hand illustration in figure 2.8. The shape is transformed from a pyramid into a diamond (see figure 2.9). Svensson argues that the least severe events are quite rare, and the majority of the events are "medium severe". The least severe events are thus located at the bottom of the diamond. Laureshyn [13] explains a theoretical framework for organising all traffic conflicts into a severity hierarchy based on some operational severity measure. The relation between severity and frequency which is used in the framework, is suggested in figure 2.9(a). The vertical position in the pyramid gives the severity level of the conflict. The surface of the pyramid slice at this specific vertical position gives the frequency of the events. An accident is explained as an unlucky coincidence of a number of factors that happen at the same time. A near-miss has a relative small safety margin to endure an additional factor compared to a well-controlled passage [13]. Therefore, the accident potential of a near-miss is relative high. These near-misses are located at the top of the conflicts slices in figure 2.9.

Laureshyn [13] states that most traffic safety indicators (surrogate safety measures) do not consider the safety of a process, but assign a severity to a certain moment during this process. The occurrences just before or after this moment are not taken into account. Besides, safety is often used as if it the only motive while moving in traffic. Other motives like efficiency and comfort are not considered, although these may influence the safety indicators measurements. Therefore, apparently severe conflicts might be the result of the road

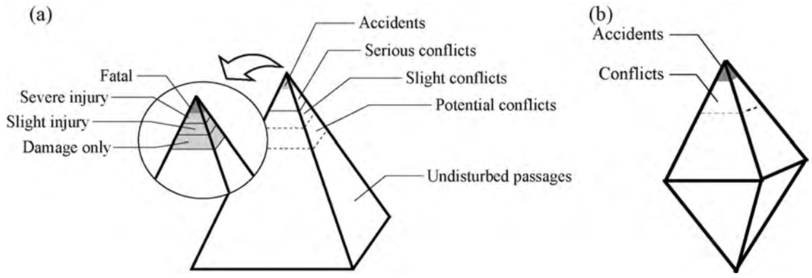


Figure 2.9: Relation between severity and frequency of traffic events; figure (a) is given by Hydén [11], figure (b) is given by Svensson. [12]

user willing to create a more efficient and/or comfortable route. With this line of reasoning, it could be argued that surrogate safety measures does not always give a proper indication of the conflict-severity. On the other hand it can be concluded that in a apparently severe conflict the accident probability is higher, since one of the road users might make an evasive action which could lead to an accident. So, each severe conflict has a high accident probability, because a relative small evasive action may already cause an accident if the conflict-severity is high.

Svensson [12] suggests that the non-serious conflicts give different information depending on how close to the serious conflicts they are located in the severity hierarchy. Events which are located just beneath the serious conflicts are characterised by closeness in time and space. Therefore, they have a strong relation to safety. Svensson argues that high severity conflicts may be positive from a safety point of view, because they are severe enough to increase awareness but not severe enough to result in accidents. It is stated that conflicts just below the "border level between severe conflicts and accidents" contribute to the learning process of road users.

Some studies searched for a direct relation between surrogate safety measures and accidents. Young [42] states in his summarizing paper that there are many studies (for example Archer [18], Cunto and Saccomanno [44] and Dijkstra et al. [45]) which conclude there is a relationship between surrogate safety measures and accidents. In order to relate surrogate safety measures to accidents, equation 2.1 is presented in the paper of Young [42]. In the equation, λ is the number of accidents expected to occur during a certain period of time, π is the accident-to-surrogate ratio and c is the number of accident surrogates occuring on a location in that time.

$$\lambda = \pi x c \tag{2.1}$$

St-Aubin [46] states that in the past many people argued against the usage of conflict analysis as a reliable safety measure. Main arguments against this approach included the costs of manual data collection, the subjectivity of interpretation or observation and the unknown link between conflicts and accident frequency and severity. St-Aubin argues that parts of the subjectivity and data collection issues are solved thanks to computers. The study concluded there is lack of agreement on the method and their guidelines, and lack of guidelines in the first place. Tarko [43] states there is still a considerable amount of work to do on surrogate safety measures. This work focusses on relating conflict frequencies to accident frequencies. Another challenge is the selection of SSM that are reliable with respect to their relationship with accidents.

As discussed above, surrogate safety measures are calculated from vehicle trajectories. Several methods may be used in order to collect vehicle trajectories, which are discussed below:

- **Filming existing locations**. On examined locations, vehicles may be filmed from different angles which makes it possible to obtain vehicle trajectories automatically. An advantage of this method is that realistic driving behaviour is measured. A disadvantage of this method is that only at existing locations trajectories can be collected. As a result, the freedom in choosing a location with certain traffic conditions and road design is limited.

- **Collecting GPS data**. Vehicles may be equipped with very precise GPS trackers, which collect vehicles' coordinates over time. Advantages of this method are that coordinates are collected automatically, and realistic driving behaviour is measured. A disadvantage is that all vehicles needed in the SSM calculations need to be equipped with the GPS trackers, which might be difficult to realize. Another disadvantage of this method is that only on existing locations trajectories can be collected. As a result, the freedom in choosing a location with certain traffic conditions and road design is limited.

- **Microscopic simulation software**. In microscopic simulation software, traffic flow is generated in which each vehicle is simulated individually. Each simulated vehicle has its own driving behaviour, which represents the varying driving behaviour in real life. The software is able to obtain vehicle trajectories from the driving behaviour shown in the simulation. Advantages of this method are that all traffic conditions and road designs can be simulated. Real life roads and road users are not required as an input for this method. A disadvantage of this method is that no real life driving behaviour is measured. Driving behaviour in traffic simulation models is derived from a driving behaviour model, which is based on assumptions. Therefore, calculating surrogate safety measures from trajectories derived from microscopic simulation software results in non-realistic measurements, as the measured driving behaviour is based on assumptions.

Microscopic traffic simulation models are intentionally developed for evaluation, management and analysis of traffic flows. The models are not developed for road safety purposes, which is a disadvantage of using this method. Conflicts always have a certain maximum level of severity in simulated traffic, so that accidents do not occur during simulation. Conflict severity in simulated traffic depends on parameters which can be adjusted in the implemented driving behaviour models. Yang [15] states that the concept of using traffic simulation models for safety issues is still a challenging topic. However, this approach has got increased attention in the last decades. Yang states that extended TCT's can be produced from simulation-based vehicle trajectories during the simulation, in order to automate conflict analysis.

An advantage of using simulation-based trajectories is that it requires least human involvement, which results in objective observations. Simulation-based analysis needs less man-power to collect and analyse data, which results in lower costs in the end. For example VISSIM is able to collect vehicle trajectories from which surrogate safety measures can be calculated. Yang [15] concludes from a literature study that VISSIM is one of the most frequently used simulation programs for performing safety evaluation.

Saccomanno [44], Young [42] and Astarita [47] state that microscopic simulation models are increasingly used for accident prediction and safety performance. However, before using these models they must be calibrated based on real-world traffic conditions in order to minimize the error between simulated and observed driving behaviour. It is important to incorporate realistic behaviour in order to capture the variability in road user performance in real world conditions [42]. Saccomanno [44] performed a calibration exercise in his study in which he compared his simulation data using six combinations of input parameters, and measured the Crash Potential Index (CPI) of each vehicle. After calibrating, the observed measure fits well within the 95% confidence interval of the values obtained from the simulation. This implies that the model is able to replicate a specific safety performance for a sample of vehicles. Astarita [47] also performed a calibration on the microscopic simulation model TRITONE. The results show that a 95% confidence interval can be achieved for the DRAC (Deceleration Rate to Avoid Collision) indicator. The two studies discussed above indicate that it is feasible to simulate realistic driving behaviour after calibration, so that safety performance of vehicles can be replicated. The summarizing paper of Young [42] concludes that existing traffic simulation models provide a flexible enough platform for safety modelling, provided that calibration of driving behaviour is performed in order to reproduce realistic driving behaviour.

Yang [15] also examines the limitations of calculating surrogate safety measures from vehicle trajectories obtained in microscopic traffic simulation software. He concludes that most of the previous performed studies are only based on a typical case study. One of the most important factors is the accuracy of the driver behaviour models in the simulation models. Many micro-simulation programs are built for traffic flow simulation in which accidents can not occur. Internal driving behaviour models generally have a quite simplified character due to a lack of knowledge [48]. The models are not sufficient enough to represent detailed and diverse drivers' interactions, which are needed for safety evaluation.

> Therefore, the models need to be used with any caution to prevent unrealistic conflict cases. Yang [15] concludes that expanding the capability of simulation software deserves more effort, although traffic simulation software such as VISSIM, Paramics and AIMSUN is frequently used. It is concluded that different simulation software has different strengths and weaknesses, which does not result in an agreement about the suitability of any simulation software for safety analyses.
>
> From literature it can be concluded that microscopic traffic simulation programs have the potential to be used for safety analysis. Since the programs essentially are used for evaluation of traffic flows, calibration is very important in order to simulate realistic driving behaviour. The most ideal scenario is the development of more detailed mathematical models, which are especially intended for road safety purposes instead of traffic flow purposes. However, simulation models provide a flexible platform for the modelling of safety, in which the driving behaviour can be adjusted to make the micro-simulation suitable for safety analysis.

Many different surrogate safety measures exist and are discussed in literature. The surrogate safety measures which are the most common and the most found in literature are discussed in the subsections below.

TIME TO COLLISION

Explanation Time to Collision (TTC) may be calculated from both the context of following vehicles and the context of lane-changing vehicles. The general form of TTC is simply understood as the closing distance to the predicted point of collision divided by the speed of both vehicles [46], which is the time required for two vehicles to collide if they continue at their present speed and along the same path [13]. The TTC in the context of lane-changing manoeuvre is defined as the difference between the end time of a vehicle's lane change and the projected arrival time of the through vehicle at the conflict point, assuming both vehicles keep their initial speed [49]. Laureshyn [13] visualized the TTC measurement (figure 2.10), in which can be seen that TTC may be calculated from different angles under which the vehicles approach.

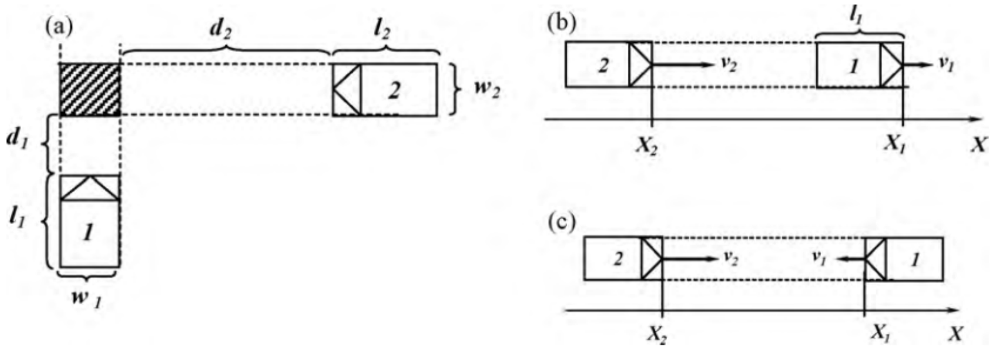


Figure 2.10: Visualization of different variants of time to collision measurements. [13]

Tak [50] and Yang [15] state that time to collision uses the time which is left before an accident occurs, in order to represent the accident-probability. Time to collision can be calculated using equation 2.2, of which the description of the components is given in table 2.2.

$$TTC = \frac{x_{n-1}(t) - x_n(t) - s_{n-1}}{v_n(t) - v_{n-1}(t)} \tag{2.2}$$

Equation 2.2 holds, assuming the following:

TTC uses the time left before a collision in order to represent the accident probability. This is based on two assumptions:

1. The two vehicles maintain their current speeds.
2. The accident potential would not arise if the leader vehicle is faster than the following vehicle.

The U.S. Department of Transportation [49] states that a low TTC indicates a high accident-probability and thus indicates an unsafe situation. The paper of St-Aubin[46] states that it is generally accepted that

Table 2.2: Full description of abbreviations from equation 2.2.

Abbreviation	Description
$x_{n-1}(t)$	Location of the leader vehicle at time t
$x_n(t)$	Location of the following vehicle at time t
s_{n-1}	Lenght of the leader vehicle
v_n	Speed of the following vehicle at time t
$v_{n-1}(t)$	Speed of the leader vehicle at time t

spatial and temporal proximity increases accident-probability. TTC is often chosen since it has an intrinsic relationship with driver reaction time, evolves continuously over the course of each conflict, is simple to calculate and relative much research has been done on this SSM. Different interpretations of the observations are possible. TTC is described by St-Aubin [46] as a measure of proximity which takes both space and time into account. Other factors which influence accident-probability are driver reaction time, visibility and vehicle performance and are represented by θ in equation 2.2. In this equation, $PC(t)$ is the accident-probability at any time t which depends on $TTC(t)$ and θ. The accident-probability increases if TTC decreases (with θ held constant), and therefore road safety decreases. This can be seen in equation 2.4, in which the accident probability is equal to 1 if TTC is equal to 0.

$$PC(t) = f(TTC(t), \theta) \tag{2.3}$$

$$PC(TTC(t) = 0, \theta) = 1 \tag{2.4}$$

The closer the vehicles, the more likely that accident mitigation factors (such as drivers' reaction time or emergency braking) alter the accident outcome. An accident location predicted with a TTC of 1 second seems much more probable than a collision point predicted with a TTC of 20 seconds. In a time span of 20 seconds, there is relative much time for trajectories to alter in order to prevent an accident. St-Aubin [46] ignores all TTC measurements higher than 50 s, as a consequence of the assumption that their predictive power is very low.

Tak [50] states that the conventional TTC has some limitations, since it is just a snapshot of a certain circumstance. TTC is for example not calculated if the leader vehicle's speed is higher than the following vehicle's speed. However, an accident potential could arise because the distance between the vehicles is not sufficient to respond to a sudden action by the leader vehicle, although its speed is higher. Besides, TTC does not estimate the accident-severity.

At merging tapers, vehicles may approach each other in many different angles. Assuming a certain approaching angle, many accident types are possible for this specific angle which can be seen in figure 2.11 which is designed by Laureshyn [13]. All possible accident types must be taken into account when calculating TTC, in order to calculate the minimum. A similar approach is given in the paper of St-Aubin [46], where two different interaction types are given. The first type is rear-end converging, if the speed of the leading vehicle is lower than the speed of the following vehicle. The second type is diagonal converging, of which different types occur which can be seen in figure 2.11. In order to calculate the critical TTC in a specific situation, all relevant accident types have to be taken into account, of which the minimum TTC measurement is the critical value.

Minderhoud and Bovy [14] proposed two extended measures, in which the TTC evolution process is extracted (see figure 2.12). The Time Exposed Time-to-Collision (TET) expresses the total time spent in safety-critical situations below the threshold value. A disadvantage of this value is that each value lower than the threshold value is assumed to have the same weighting in the calculation. In order to reflect the impact of the TTC value, the TIT (Time Integrated Time-to-collision) indicator is introduced. The TIT evaluates the entity of the TTC lower than the threshold TTC. By using the TIT value, one is able to better indicate unsafe situations in comparison with TET. For example, the conflict measured between t_1 and t_2 has a relative high accident-probability compared to the conflict measured between t_5 and t_6, as illustrated in figure 2.12. Minderhoud and Bovy [14] state that "a high TIT value means a large exposition time to duration-weighted unsafe TTC-values, which is negative for road safety". In figure 2.12, TIT is illustrated by the dark surface.

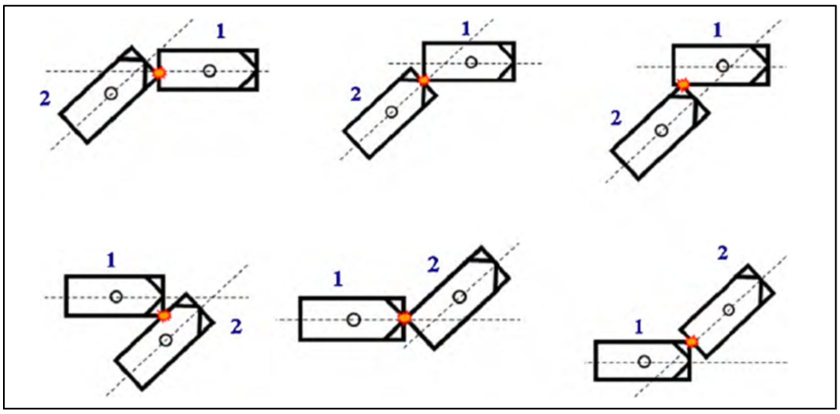


Figure 2.11: Possible collision types for the same approach angle. [13]

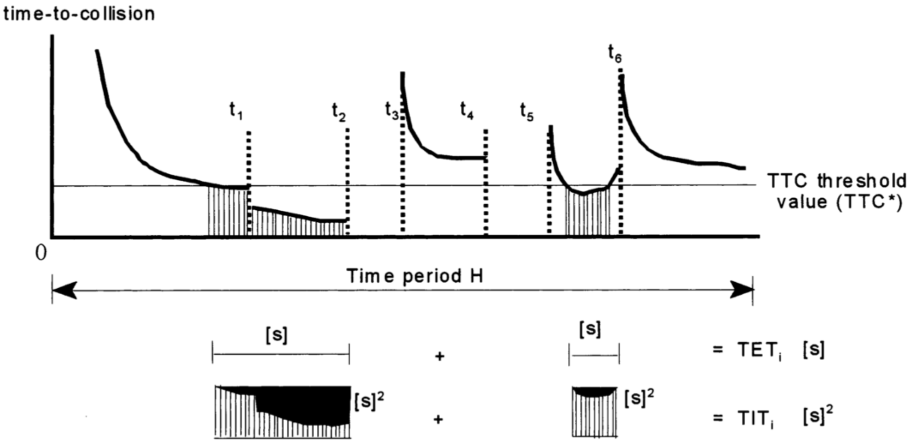


Figure 2.12: Visualization of TET measurements and TIT measurements, extracted from a TTC profile. [14]

Another extension of TTC is proposed by Yang [15], and is called MTTC. This value takes into account the acceleration of both interacting vehicles. With this value, it is possible to calculate a value if the preceding vehicle has a higher speed than the following vehicle. This is an advantage in comparison with the traditional TTC, in which this is not possible. Yang compares MTTC to the traditional TTC in a case study. It shows that MTTC gives more conflicts, since it takes into account acceleration and deceleration effects.

Typical critical values Many studies tried to determine a critical safety treshold for TTC. An overview of the critical values is given in table 2.3. Yang [15] states that in general, a TTC lower than the perception and reaction time should be considered risky. Various different critical values may be argued due to the variance of driver perception, reaction time and other driving conditions. Therefore, there is no unique threshold value for TTC or one of its extensions. It is not exactly clear which value can be defined as "safe" and which value can be defined as "unsafe", although low values can be interpreted as more unsafe than high values. Typical critical values of the TET, TIT and MTTC are not found, probably because these values are relative new and not widely accepted in literature.

Table 2.3: Critical values for Time To Collision.

TTC [s]	Value explanation	Reference
4	Used to discriminate between cases where drivers unintentionally find themselves in a dangerous situation from cases where drivers remain in control	Hirst and Graham [51]
2	safe-critical value	Minderhoud and Bovy [14]
3	For developing of Rear-End Collision Avoidance Systems	Hirst and Graham [51]

Validation Yang [15] states that TTC is a frequently used measure. This is because of theoretical issues, since road users are always on a conflicting path when considering TTC. This surrogate safety measure can be used in relative many types of interactions. Besides, TTC is used for many automobile accident avoidance systems or driver assistance systems as an important warning criterion.

However, there are also some shortcomings in the use of TTC as a surrogate safety measure. For example, the value of TTC can not predict the accident severity. TTC measurements can not differentiate between the severity of two conflicting events with the same TTC but with different absolute speeds. Determining the evolution process of the distance gap and speed gives more clarity about the values. However, measures including these factors are not widely tested and validated in literature.

Yang [15] studied the link between MTTC measurements and actual accidents. To do so, the conflict probability (CP) is defined as a function of MTTC. Since there are different possible conflicts, the CP's of these conflicts are defined separate. The overall potential conflict risk (CR) is the sum of the CP's multiplied by the frequency of the specific conflict. From a field study, it is concluded that the conflict risk is in "good agreement" with actual accident data in most sections. A linear relation between the conflict risk and accident data is found, and can be seen in figure 2.13. In this figure, a clear link can be seen between conflict risk and actual accident data.

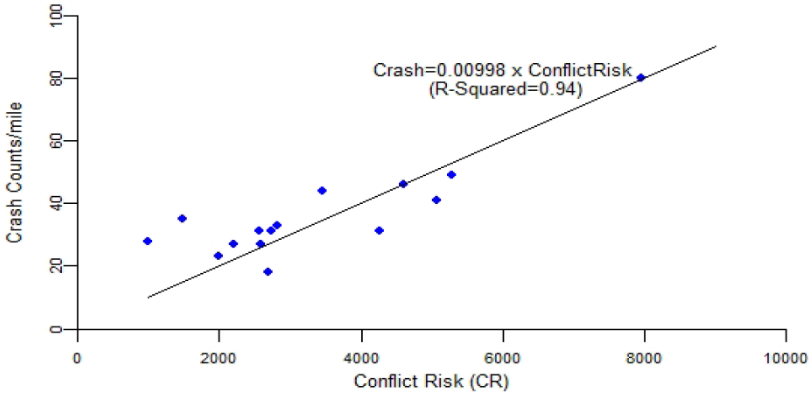


Figure 2.13: Relation between conflict risk and accident data [15].

POST ENCROACHMENT TIME

Explanation Post encroachment time (PET) is defined as the time between the first vehicle leaving the common spatial zone and the second vehicle arriving at it [13] (see figure 2.14). In this figure, PET is defined as $t_2 - t_1$. In other words, this is the minimal delay of the first road user which will result in a collision course and a collision. This holds, assuming vehicles continue with the same speeds and paths. In figure 2.15, lines I and II represent vehicle trajectories. A “delay” of vehicle I is illustrated by shifting the line to the right, until it overlaps line II which indicates an accident. PET is equal to the distance over which the line is shifted. Archer [18] states that PET is used to measure situations in which two vehicles which are not on a collision course, pass over a common spatial point or area with a temporal difference that is below a predetermined threshold.

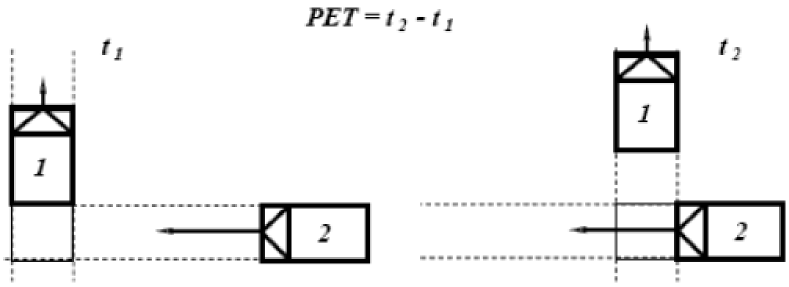


Figure 2.14: Schematic representation of the post encroachment time calculation. [16]

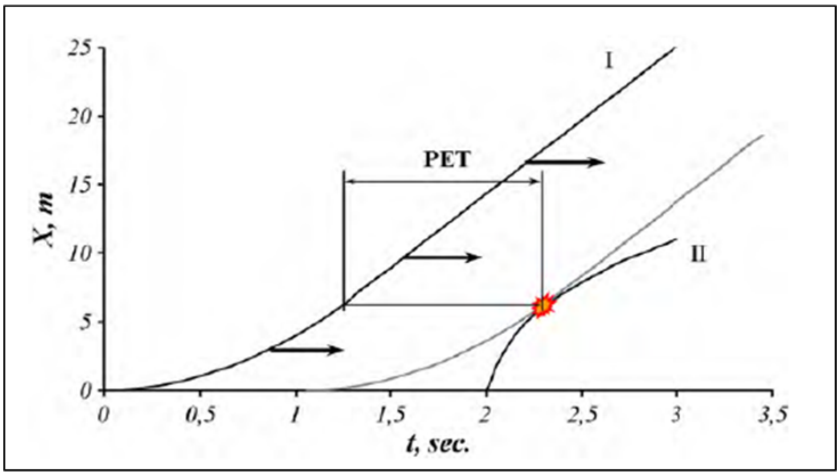


Figure 2.15: Schematic representation of the calculation of the post encroachment time from vehicle trajectories. [13]

Zheng [17] defines the PET during a lane change maneuver as the time difference between the end of the leading vehicle leaving the encroachment line and the front of the following vehicle arriving at the encroachment line. The encroachment line is a virtual line perpendicular to the lane dividing marker and crossing the intersection point of the lane dividing marker and the lane change trajectory (see figure 2.16). In Zheng's study, the lane dividing marker is used for convenience of measurement, although it causes small measurement errors. In figure 2.16, four different situations are shown in which PET is equal to 0. In the schematic representation, it can be seen that for conflicts O-A and O-C vehicles are overlapping, while for conflicts O-B and O-D there still is some longitudinal space between two conflicting vehicles. The measurement error is less than 0.017 s, provided that the vehicles' speed is higher than 60 km/h.

The main difference between PET and TTC is the absence of the collision course criterion [18] in the PET calculation. The concept of PET is solely useful for measuring safety critical events if crossing vehicle trajectories are involved. Events with similar (final) trajectories are better suited to the TTC-concept [18], because there will always be a collision course if the speed of the following vehicle is higher than the speed of the preceding vehicle. PET measurements require a fixed projected point of collision, rather than one that changes which is the case in an unsafe rear-end or merging interaction [18].

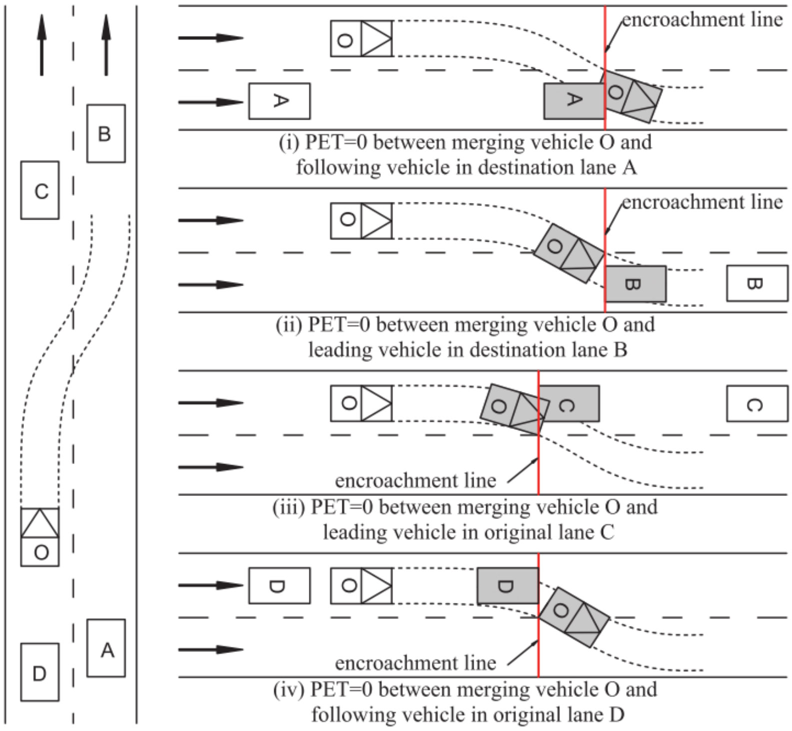


Figure 2.16: Examples of lane change configurations for which the post encroachment time is equal to zero. [17]

Typical critical values Not many critical values of the PET are given in literature. Two are found and can be found in table 2.4.

Table 2.4: Critical values for Post Encroachment Time.

PET [s]	Value explanation	Reference
1.5	critical	Archer [18]
1	critical	Kraay [52]

Validation A disadvantage of the PET is the fact that the definitions are difficult to apply if vehicles do not cross at a straight angle. In situations where a pair of vehicles cross at a straight angle, an accident would occur if the vehicles are in the common zone at the same time, which can be seen in figure 2.14. It is possible that both vehicles appear in the common zone at the same time, but no accident [13] occurs, which is illustrated in figure 2.17. At merging tapers, vehicles approach each other mainly under a small angle and often might be in the common zone without having an accident.

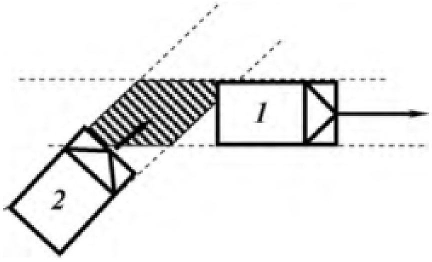


Figure 2.17: A disadvantage of the post encroachment time; two vehicles appear in a common zone but avoid collision. [13]

PET is relative easy to extract from trajectory data since no relative speed data and distance data are needed. Therefore, PET is less resource-demanding than TTC. Besides, no constant recalculations at each time-step are needed. At the same time, this simplicity is a drawback of this measure. Since the speed and distance are not measured for the purpose of determining this value, there is no possibility to accurately compare the relative severities of PET events [18].

TIME ADVANTAGE

Explanation Time Advantage is introduced by Laureshyn [13], and is an indicator which is used to describe situations where two road users pass a common spatial zone. However, the road users pass the common spatial zone at different time steps and thus a collision course is avoided. Time advantage can be seen as an extension of the PET. The PET defines the time between the first vehicle leaving the common spatial zone, and the second vehicle arriving at the common spatial zone. The calculation of Time Advantage is similar to the calculation of PET, which can be seen in figure 2.15. Time Advantage is defined in the same manner, but using *predicted* travel lines instead. The position of the contact between the two lines depends on the line's shape, and thus on the moment at which the prediction is made. In contrary to PET, Time Advantage is calculated again in each time step in order to determine the predicted trajectories in each specific time step.

The measurement of Time Advantage itself is not sufficient to indicate the collision risk, since it is not clear how soon the encroachment will occur. Even if Time Advantage is small at a certain moment, road users may have plenty of time to adjust their trajectories. An indicator is introduced in order to describe the nearness of the encroachment, and is called T_2. One could argue that the second arriving road user is the most safety-relevant of the two road users involved in an encroachment [13]. Independent of the actions of the first road user, the second road user is the one who arrives last, and thus has the most time to take an evasive action. If the moment of the first road user leaving is of interest, the final measure can easily be calculated as $(T_2 - TAdv)$.

Typical critical values Only one typical value for TA is found in literature. As the calculation of the TA is similar to the calculation of PET, the critical values of PET may be used as critical values for TA.

Table 2.5: Critical values for Time Advantage.

TA [s]	Value explanation	Reference
> 2-3	Values for normal traffic conditions	Laureshyn [13]

Validation Time Advantage is an extension of PET, but it uses predicted travel lines instead of actual driven travel lines. As a result, Time Advantage may be measured in each time step. Besides, an indicator is introduced which describes the nearness of the encroachment. On the other hand, TA is not widely discussed in literature and therefore it is not proved to be a reliable measure.

TIME HEADWAY

Explanation Time Headway (THW) is comparable to TTC, however for this measure no predicted accident is needed for vehicles following each other. Laureshyn [13] explains that THW is a measure that describes the actual distance between road users expressed in time units. Vogel [53] states that THW is measured as the time between the moment of the rear-end of the first vehicle passing a certain point on a road and the front of the following vehicle arriving at that point. Due to the geometric design of the vehicles and the path of the vehicles, there are several possible measure points. The possibilities for the same approach angle are similar to the possible collision types for TTC, see figure 2.11. The minimum of these possibilities is the critical THW measurement. It has a weaker connection to collision risk compared to TTC, since it only considers the spatial proximity between vehicles, but not the relative speeds.

The following example is given in the paper in order to explain how potential risk can be detected from THW: assume two vehicles following each other on the same course and with the same speed, without an existing collision course. If the first vehicle starts braking, the vehicles could possibly enter a collision course and the pace of the TTC-decrease highly depends on the size of the THW. Therefore, THW influences the probability of TTC reaching low values when a vehicle gets into a collision course [13]. The Time Headway is formulated as follows:

$$THW = t_i - t_{i-1} = \frac{\Delta d}{V_f} \tag{2.5}$$

Definitions for THW which are given in relevant studies are quite similar to each other. Savino [54] studied many papers in order to get an overview of definitions which are used for driving performance measures. Based on this study it can be concluded there are two deviations between the given definitions. The first deviation is whether the length of the leading vehicle is taken into account, so whether THW is calculated between the two front bumpers or between the rear-end bumper of the leading vehicle and the front bumper of the following vehicle. Besides, Yang [15] states that the two consecutive vehicles must travel in the same lane. However, Savino [54] concludes from 18 definitions that this is not a requirement for calculating THW.

Typical critical values Critical values for THW are given in many studies, and an overview of the values can be found in table 2.6.

Table 2.6: Critical values for Time Headway.

THW [s]	Value explanation	Reference
<1	Crash involved drivers were more likely to follow with time headways smaller than 1	Evans [55]
<0,7	Described as "dangerously closely"	Helliar-Symons [56]
<1	Described as "imprudently closely"	Helliar-Symons [56]
<0,6	Described as "danger zone"	Ohta [57]
<0,7	Median choice for a minimum safe THW	Taieb-Maimon [58]
<2	Should not considered safe enough to prevent possible conflicts with the leading vehicle	Evans [59]
<2	Tailgating, contributing cause of rear-end accidents	Michael [60]
>2	Recommended by many road administrations in European countries	Vogel [53]

Validation Time Headway is a surrogate safety measure which is widely discussed and accepted in literature. THW may be measured for a pair of vehicles which trajectories cross under each possible angle. On the other hand, the relative speeds are not taken into account when calculating THW. If the preceding vehicle has a high speed compared to the following vehicle, a low THW measurement does not automatically indicate an unsafe situation. Therefore, THW has a weaker connection to collision risk than TTC [13]. Still, THW can be used for the detection of potential risk at earlier stages of an encounter. Evans [55] and Michael [60] conclude that small THW measurements are directly linked to accident frequency.

TIME TO ACCIDENT

Explanation Hydén [11] describes the Time To Accident (TTA) as "the time between an evasive action was taken and an accident would have occurred if the conflicting road users had continued with unchanged speeds and direction". The difference with TTC and THW is that TTA is only calculated if an evasive action is taken. The minimal TTA for a vehicle which is braking at its maximum is calculated as follows:

$$TTA = \frac{\Delta d}{v_i} \tag{2.6}$$

In equation 2.6, Δd represents the distance to the collision location at the start of an evasive manoeuvre, and v_i is the initial speed of the following vehicle. Based on equation 2.6, a graphic representation of the relation between speed and TTA is made which can be seen in figure 2.18. In the right-hand figure, a safety margin of 0,5 seconds is implemented. The red line indicates the boundary between serious and non-serious conflicts.

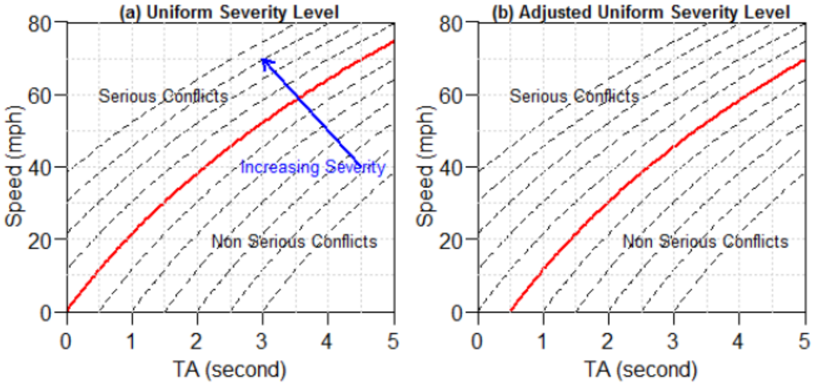


Figure 2.18: Severity level which is determined based on speed and time to accident. [18]

Typical critical values Solely one critical value is found in literature and is stated in table 2.7. In upfollowing studies TTA's critical values are given, but depends on speed (see figure 2.18).

Table 2.7: Critical values for Time To Accident.

TTA [s]	Value explanation	Reference
1,5	Used to distinguish serious conflicts and slight conflicts	Amundsen and Hydén [11]

Validation No clear relation between TTA and accident data is found in literature. However, some studies conclude that low TTA values are directly linked with serious conflicts which is illustrated in figure 2.18. An advantage of this measure is that it can be calculated regardless of the angle under which vehicles approach. This SSM is similar to THW, but TTA is only calculated if an evasive action is taken.

Deceleration Rate

Explanation The Deceleration Rate is the rate at which a vehicle must decelerate in order to avoid an accident. Higher deceleration rates indicate a higher accident-probability. The US Department of Transportation [49] states that the initial DR is a useful measure to indicate the potential severity of the conflict event. The paper indicates the Deceleration Rate as one of the most important surrogate safety measures.

Tak [50] states that human-centered design is essential when estimating the potential collision risk, because human-related parameters are the direct contributors to accidents. Reflecting human driving behaviour is stated as being the key factor in improving the precision of collision risk estimation. Driving behaviour can for example be expressed with acceleration and deceleration of a following vehicle corresponding to its leaders' movement. A following vehicle catches up with the leader vehicle by accelerating until the collision risk becomes larger than a certain treshold or the desired speed is reached. After that, if the spacing increases and the collision risk drops below a certain treshold again, the driver accelerates again in order to keep the appropriate spacing. Although this is not mentioned in the paper, this process is similar to the car-following model by Wiedemann.

In some papers DR is extended to the Deceleration Rate to Avoid the Crash. Saccomanno [44] explains that this measure considers the role of speed differentials, deceleration and distance. DRAC is a function of time/space and deceleration profiles experienced by vehicle pairs. Saccomanno [44] states that it reflects a deceleration required to come to a timely stop or attain a matching lead vehicle speed to avoid a rear-end accident. DRAC is calculated using the following formula:

$$DRAC_{i,t+1} = \frac{(V_{i,t} - V_{i-1,t})^2}{(X_{i-1,t} - X_{i,t}) - L_{i-1,t}} \tag{2.7}$$

In equation 2.7, V represents the velocity of the vehicles, i represents the following vehicle, $i-1$ represents the leading vehicle, X represents the position of the vehicles, L represents the vehicle length and t represents the time interval.

Saccomanno [44] adds that the conventional DRAC measure fails to accurately reflect traffic conflicts and hence identify potential accidents. This is caused by the fact that DRAC does not take into account the vehicle's braking capability and traffic conditions. For example, wet pavement has relative low friction and thus the DRAC value becomes more critical. In order to include this effects, Saccomanno introduced the Crash Potential Index (CPI). This measure gives the probability that a given vehicle's DRAC exceeds its maximum available deceleration rate (MADR) or braking capability in each time step. MADR is vehicle- and scenario-specific, and therefore different values must be specified for each vehicle. The CPI is can be calculated using formula 2.8.

$$CPI_i = \frac{\sum_{t=ti_i}^{tf_i} P(DRAC_{i,t} > MADR_{i,t})\Delta t b}{T_i} \tag{2.8}$$

In this formula, CPI_i is the crash potential index for vehicle i, ti_i is the initial time interval for vehicle i, tf_i is the final time interval for vehicle i, Δt is the observation time interval (s), T_i is the total simulated time for vehicle i(s). The term b is a binary value which is 1 if $DRAC_{i,t.0}$>0, and thus CPI only exists if the following vehicle approaches the leading vehicle.

Typical critical values Gettman [49] and Tak [50] conclude that the occurence of a relative high DR is relative unsafe. No typical values for DR are found, but there are two values found for the extended measure DRAC which are presented in table 2.8.

Table 2.8: Critical values for Deceleration Rate.

DR $[m/s^2]$	**Value explanation**	**Reference**
3.4 (DRAC)	maximum comfortable deceleration rate	Astarita [47]
> 3.35 (DRAC)	vehicle in a serious conflict	Archer [18]

Validation Tak [50] states that abnormal longitudinal driving behaviour such as severe deceleration is highly related to accidents. A severe deceleration measurement may be considered as near-accident, which has a strong relationship with actual accident-probability. The paper also states that severe deceleration occurs if a road user has failed to detect dangerous situations on forehand, and thus has failed to adjust her own speed on time. The measure reflects the following vehicles' deceleration required to avoid a rear-end accident. High Deceleration Rates can be seen as abrupt movements which are an indication of unsafe situations.

2.3.3. DRIVING SIMULATORS

As discussed in the previous section, one of the methods to measure road safety is to calculate surrogate safety measures from vehicle trajectories. Vehicle trajectories can be obtained from different sources such as GPS tracking, filming existing locations and microscopic simulation software. Another option is to obtain vehicle trajectories from driving behaviour which is performed by participants in a driving simulator. In driving simulators, it is possible to let a group of participants drive in an environment in which traffic conditions and road design is controlled by the researcher. The for the study desired road design may be combined with the desired traffic conditions such as traffic flow and traffic composition. Since this method may be interesting as a data collection method in this study, the method is discussed in more detail in this section.

DATA TYPES DERIVED FROM DRIVING SIMULATORS

Many different data types may be obtained from a driving simulator, in order to assess road safety. Examples of data types which can be obtained from a driving simulator, next to vehicle trajectories, are given in the remaining of this section.

Vehicle trajectories As discussed in section 2.3.2, vehicle trajectories which are needed to calculate surrogate safety measures may be obtained from microscopic traffic simulation software. A major point of discussion regarding this method is that the driving behaviour in traffic simulation software is derived from behavioural models. These behavioural models are based on assumptions, and therefore non-realistic vehicle trajectories are obtained. This is described by the Dijkstra [45]: "Conflicts in a simulation model are not the same as actual conflicts observed on the street. In a model, vehicles do nothing more than follow a known route and react to other vehicles in a programmed manner. A real behavioural component is not present."

However, a driving simulator may be used in order to obtain realistic vehicle trajectories. Participants in a driving simulator drive over a controlled geometric design under controlled traffic conditions (e.g. traffic flow and traffic composition). One of the vehicles in the simulated traffic flow is controlled by the participant, and therefore a realistic trajectory for that vehicle is collected. Traffic may be simulated with several programs, which contain a variety of behavioural models.

The participant's trajectories obtained in a driving simulator are used to calculate surrogate safety measures. By doing this, calculations are performed with trajectories which are obtained from realistic driving behaviour. The participants' driving behaviour is influenced by the simulated vehicles' behaviour, and therefore the behavioural models in the simulation programs must be as realistic as possible. As discussed in section 2.3.2, calibration steps can be done in order to make the driving behaviour in models more realistic.

Eye-tracking Specific electronic tools are availabe which can track the participants' eyes during for example a driving simulator experiment. It is recorded on which objects and locations the participants focusses. With this method, it is possible to study whether road users get distracted from their driving task by for example in-car systems and objects in the environment. Savage et al. [61] found several studies which measured eye movements such as blink frequency and longer blink durations. Results demonstrated increased blink rates along with longer blink durations in high cognitive load conditions when compared to low load conditions.

Heart rate During specific driving simulator experiments, the participants' heart rate may be measured using a heart rate monitor. This method is commonly used in sports and for medical purposes. Relative high heart rates indicate stress, which might arise from unsafe driving behaviour such as abrupt steering, deceleration and acceleration. A relative low or normal heart rate indicates a relative low stress-level, which is an indicator for ordinary traffic situations in which no evasive actions need to be performed. Tozman et al. [62] exposed a participants group to three simulated driving tasks that differed in their demand levels. During the tasks, the participants' heart rates were measured and flow (a pleasant state of absorption during a challinging activity) was measured after the experiment by means of a questionnaire. The study shows the relationship between heart rate variability and flow in adults exposed to tasks with different demand-levels.

ADVANTAGES OF DRIVING SIMULATORS

Obtaining vehicle trajectories using driving simulators has several advantages compared to obtaining vehicle trajectories from real life traffic. The advantages are mentioned below.

Controllability When measuring driving behaviour from real life traffic, one is dependent on the circumstances on the specific location such as weather conditions, road design and traffic conditions. Consequently, performing an experiment multiple times under exact the same conditions is very difficult or even impossible. For example, weather conditions and traffic conditions change over time, which influence driving behaviour and thus experimental results. Besides, the diversity of road designs on existing motorways is limited which limits the choice for experiment locations.

In driving simulators, one drives in a virtual vehicle in a virtual environment. An advantage of this is that the weather conditions, road design and simulated driving behaviour can be manipulated depending on the research goals [63]. If purpose-developed scenarios are used, such as in a driving simulator, it is possible to practice a large number of scenarios per time unit compared to experiments with real life vehicles on public roads. Assuming that many external factors affect driver's behaviour, it is beneficial to create standardized driving tests in which the conditions are exactly the same for each driver. In this way, results are obtained under exact the same conditions.

Data collection An advantage of driving simulators is the ease of data collection during the experiment. The simulated vehicle as well as the other traffic and environment is generated by computers, which makes it easy to collect vehicle's coordinates in each time step. Collecting vehicles' location is much more difficult to obtain very precise location data. In real life traffic, GPS trackers and film material may be used in order to obtain trajectories. However, the accuracy and efficiency of the collected data is less compared to the driving simulator's data. For example measuring vehicle's lateral position is challenging since it requires visible lane markers while weather conditions, reflections and shades affect the quality of the measurement [64]. This data can be collected more accurate using a driving simulator.

Possibility of encountering unsafe driving conditions Driving simulators can be used for training and research of unpredictable and unsafe situations which are inappropriate to practice in real traffic. This may be applicable for collision avoidance or risky driving, which is relative unsafe for the driver and other road users. Using a driving simulator, dangerous driving tasks can be performed in a forgiving environment which makes it possible to do research without the exposure to risk, which would be the case when performing similar research in real life traffic. Allen [65] states that experienced drivers have a relative low accident-probability compared to inexperienced drivers. This gives another opportunity for driving simulators, as driver's experience may be increased by driving in a driving simulator.

DISADVANTAGES OF DRIVING SIMULATORS

Obtaining vehicle trajectories using driving simulators has several disadvantages compared to obtaining vehicle trajectories using real life traffic. The disadvantages are mentioned below.

Physical validity (fidelity) De Winter [63] states that low-fidelity simulators may evoke unrealistic driving behaviour, and therefore produce invalid research outcomes. Participants may become demotivated by a low-fidelity driving simulator and prefer real vehicles or a more high-fidelity driving simulator instead. The fidelity of a driving simulator is for example determined by the realism of the environment and vehicles' driving behaviour realism, and the realism of the driving simulator's vehicle compared to a real life vehicle. In almost all instances, the simulated vehicle's behaviour is static, and does not react on the driving behaviour of other vehicles such as the driving simulator's vehicle. The realism of the simulated environment and driving simulator's vehicle is limited by the available resources and budget. The participant's driving behaviour is among others determined by the conditions mentioned above. Thus, the fidelity of the simulated vehicles, driving simulator's vehicle and simulated environment is very important in order to obtain realistic data.

Besides, participants in a low-fidelity environment might not imagine themselves in a real vehicle, which may result in a lower sense of safety. Real danger and the real consequences of actions do not occur in a driving simulator, which may result in a false sense of safety, responsibility and competence. As a result, one's reaction on dangerous situations might be different in a driving simulator than in real traffic.

Investing in resources in order to increase fidelity is not necessarily desirable, since it increases the complexity of the device and might bother experimental control. Lee [66] states that increasing fidelity dilutes training purposes and can make people sick. Sometimes, abstractions or deliberate deviations from reality yield valid results [66] [67]. Rudin-Brown [68] states that a lower-fidelity simulator may be entirely adequate for the underlying purpose of a research or training program. The level of simulation realism which is needed depends completely on the underlying purpose for choosing a simulator in the first place.

Behavioural validity Another type of validity is the behavioural validity, and relates to the comparison of driver's performance in the simulator versus performance in the real world. It is often presumed that behavioural validity is closely correlated with a simulator's fidelity, but this is not necessarily the case. It is possible for a high-fidelity driving simulator to have the same behavioural validity as for a low-fidelity driving simulator [68]. However, driving behaviour in a driving simulator is never be similar to the driving behaviour in a real vehicle, because the vehicle's characteristics, road environment and other vehicles' behaviour is a replication of the real world.

It is important that a driving simulator's behavioural validity is within an acceptable range, if results from driving simulation research are used as the basis for informing real world road safety policy. The most effective way to accomplish this is to compare driving behaviour of real world traffic to driving behaviour observed in a driving simulator. The degree to which a driving simulator generates the same numerical values of driving behaviour observed in real world is called its *absolute validity*. The degree to which any changes in those measures of driving behaviour are in the same direction, and have a similar magnitude as those in the real world, is known as the driving simulator's *relative validity* [68].

As mentioned in the previous section, both physical validity and behavioural validity are often an issue when using a driving simulator for research purposes. When interpreting results of a driving simulator study, it is important to know how the simulator's performance relates to real traffic performance. Knapper [69] found several methods which can be used for validation. It can be concluded that validation results can be obtained by comparing driving performance in the simulator to driving performance in real traffic. Besides, self-report tests (questionnaires) can be used, as well as result comparisons with accident databases and other driving simulators.

Simulator sickness Simulator sickness is caused by the *sensory conflict theory*, which states that simulator sickness rises when visual, vestibular and somatosensory (e.g. registration of touches) information are at variance with each other. Klüver [70] states that the incidence of simulator sickness might threaten user acceptance and behavioural validity of a driving simulator. Simulator sickness symptoms may negatively affect the usability of simulators for research purposes, as the results are influenced by this phenomenon.

In the past years, several studies are dedicated to simulator sickness, and how to preclude this phenomenon. From these studies, Klüver [70] concludes that a moving-based simulator was found to alleviate simulator sickness symptoms compared to fixed-base simulators. This is the result of better matching visuals and actual physical movements: the vestibular system is less disordered compared to situations in which no movements are registered by the human body. Besides, it is found that relative few simulator sickness symptoms are registered in simulators with a relative full-scale vehicle mock-up (e.g. realistic dashboard, steering wheel, pedals etc.).

Besides, Klüver [70] noted the following points regarding simulator sickness:

- Higher temparatures are associated with a higher incidence of simulator sickness. Temperatures under 21 degrees Celsius are recommended. Also air humidity is often thought to be associated with simulator sickness.
- Avoiding hard braking manoeuvres reduces sickness rates.
- It is unclear if the presence of curves in the road design is significantly associated with simulator sickness, as contrary conclusions are drawn in different studies. One could argue that sharp curves create relative much disorder in the vestibular system, which is for example concluded in the paper of De Winter [63]. However, not all studies share the same conclusion about this topic.
- Absolute driving speeds are positively correlated with simulator sickness symptoms.
- Several studies report high simulator sickness scores from females compared to males. However, the gender difference might also be caused by males which are less willing to report symptoms compared to females.
- The correlation between driver age and simulator sickness is inconsistent. Some studies report stronger sickness symptoms for older drivers, as other studies conclude the opposite or even no effect.
- It is found that operator experience (e.g. hours spent driving in a vehicle) is correlated with simulator sickness: experienced operators are more susceptible to simulator sickness than inexperienced operators.

2.3.4. QUESTIONNAIRE

Up to now in this chapter, solely objective methods to measure road safety have been discussed. Accident data and surrogate safety measures may be used to determine road safety. In order to also understand road user's perception of road safety, a subjective method such as a questionnaire may be used. A questionnaire is a research instrument which consists for example of questions and statements in order to gain information from the respondents. In road safety studies such as this thesis, questions and statements about specific traffic conditions and road design may be implemented.

An example of a study in which a questionnaire was used in order to measure subjective road safety, is in the study of Grontmij [2]. In this study, road users which drove on two merging tapers received a questionnaire sent home based on vehicle registration. This questionnaire was an addition to video registration analysis in which objective road safety was measured. A unique result from this questionnaire was for example that road users intentionally chose for the right-most lane, to avoid the tapered lane. Such data can not be measured from methods such as accident data analysis and using surrogate safety measures, and therefore a questionnaire is a useful additional method.

As discussed in section 2.3.3, driving behaviour performed in a driving simulator will never be exactly the same as driving behaviour in real traffic. Behavioural validity of the driving simulator determines how realistic the performed driving behaviour is compared to real world driving behaviour. The concerns regarding driving simulators are also mentioned by Burnett [71], citing: “For any driving simulator, the challenges relate to how the results derived from a simulator show a true reflection of reality, the level of fidelity to consider in certain simulation studies, behavioural realism and simulation experience - feeling of immersion (The physical extent of the sensory information provided as function of the enabling technology [72]), presence (the subjective experience of being in one place or environment, even when one is physically situated in another [73]), control, induced motion sickness etc. To evaluate drivers’ simulation experiences, there is a need to relate the factors of fidelity, validity, realism, and the perceived and observed driving behavior as well as the virtual reality experience.” The study of Witmer [73] states that the effectiveness of virtual environments has often been linked to the sense of presence reported by users of the virtual environments. When performing a driving simulator experiment, in most cases the experimental set-up is not exactly the same as any real-world situation. Therefore, often no real-world trajectories are available to compare with trajectories obtained in a driving simulator. To still give an assessment on the driving simulator’s realism, a questionnaire may be performed. In many studies, questionnaires are developed which may be added to a driving simulator experiment, for example by Burnett [71], Witmer [73] and Kyriakidis et al. [74].

Drivers’ characteristics such as gender, age and occupation may also be a factor which determines driving behaviour. A questionnaire may be used in order to collect such socio-demographic data. Statistical relationships between socio-demographic data and driving simulator’s results might be found. For example, it might be feasible that relative young participants have more affinity with driving in virtual reality. Driving simulator results might also be determined by for example driving experience, involvement in accidents and length of drivers license ownership. Besides, socio-demographic data can be using to verify whether the chosen participants’ sample reflects the driving population in the studied country or region.

2.4. CONCLUSION

Guidelines on the geometric design of merging tapers on Dutch motorways are given in the ROA [21]. It can be concluded that no clear underpinning of these guidelines is available. Neither an underpinning is available of the presumption that a merging taper is less safe than the standard geometric design. In the British and US literature, geometric designs similar to a merging taper are found, but the number of guidelines is limited and not underpinned. A geometric design which is similar to a Dutch merging taper was applied on German motorways as an on-ramp. However, this geometric design is no longer applied after 1976 because of high accident rates on these locations. Overall, it can be concluded that geometric designs similar to the Dutch merging taper are seldom described in literature. The literature did not provide underpinnings for the guidelines given in Dutch design guidelines.

Road safety is defined as the safety level in road traffic, and is a large topic in Dutch society since approximately 1970. Two types of road safety exist which are subjective road safety and objective road safety. Subjective road safety is the personal feeling of being unsafe in traffic. Objective road safety is based on numbers such as the number of accidents, and is often used to express road safety. The probability for a road user to be involved in an accident is a function of the exposure to risk. Risk is defined as the probability per amount of travel to be involved in an accident, and exposure is defined as the amount of travel. The exposure to risk and thus road safety depends on many factors such as traffic conditions and road design.

From literature it can be suspected that taper-length affects road safety. A relative short taper-length causes relative small accepted gaps which are relative unsafe. A first analysis shows that more than half of the merging tapers present on Dutch motorways have a too short taper-length according to the design guidelines. Based on the literature, it is expected that this deviation from the design guidelines has a negative effect on road safety. If the traffic volume on a certain location is relative high, relative many vehicles are present in a road section and thus they drive closer to each other. Therefore, a high traffic volume has a negative effect on road safety. The presence of heavy vehicles also has a negative effect on road safety, because they block relative much space. Vehicles approaching on the tapered lane must change lane to adjacent lanes, in which the space is blocked by heavy vehicles. This may result in relative small accepted gaps and is thus relative unsafe. A relative high absolute speed causes a relative high accident probability and therefore is relative unsafe. Also drivers’ characteristics affect road safety. For example age affects road safety, since young drivers are in general inexperienced drivers. Weather conditions such as a lows standing sun, rain and wind also have a negative effect on road safety.

Several data types are available to determine road safety (figure 2.19). The usage vehicle trajectories and registered accidents are objective data types. The analysis of registered accidents is a re-active method, since accidents must have occurred before road safety can be assessed. Several studies mentioned another disadvantage of this method, which is the lack of available data and low quality of the data. A more pro-active method is the usage of vehicle trajectories from which surrogate safety measures may be calculated. Surrogate safety measures indicate the conflict-severity between a pair of vehicles. In several studies, critical surrogate safety measurements were related to the number of accidents, and thus objective road safety. It can be assumed that severe conflicts have a higher accident-probability compared to non-severe conflicts, since the margin to endure an additional factor is relative small in severe conflicts. Surrogate safety measures are calculated from vehicle trajectories, which can be collected in different ways such as GPS, video material and microscopic traffic simulation software. An advantage of GPS and video material is the realism of the measured driving behaviour, as microscopic traffic simulation software generates trajectories from a driving behaviour model which is less realistic than real life driving behaviour. An advantage of using microscopic traffic simulation software is that traffic can be simulated in all possible traffic conditions and road designs. GPS and video material is generated from existing locations on which traffic conditions and the road design can not be controlled.

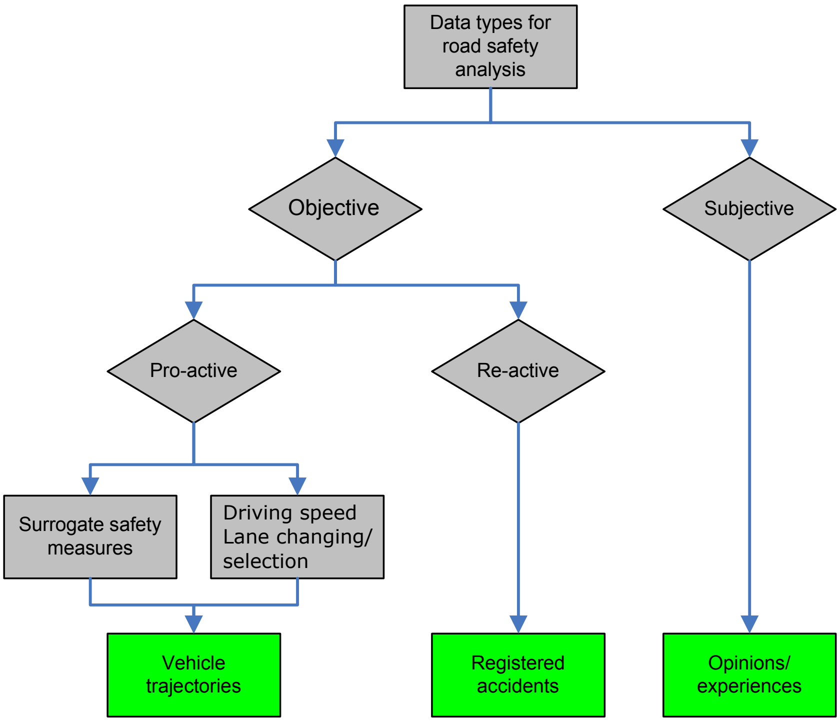


Figure 2.19: Data types which may be used for measuring road safety.

Vehicle trajectories may also be collected in a driving simulator. One of the advantages of using a driving simulator is that one has the freedom to vary in road design and traffic conditions without creating unsafe situations on public roads. Besides, data collection in driving simulators is relatively straightforward compared to GPS and video material. Next to vehicle trajectories, also other types of data may be obtained from a driving simulator, such as eye-tracking data and the participant's heart rate. Issues involving the usage a driving simulator are the physical validity and behavioural validity of the driving simulator. Physical validity can be determined by the realism of the environment and vehicles' driving behaviour, as well as the realism of the driving simulator's vehicle. Behavioural validity gives information about whether the driving behaviour performed in the driving simulator is similar to driving behaviour performed in real-life. This may be determined by comparing both driving behaviours, but often this data is not available. An alternative for this method is to use a questionnaire to measure the driving simulator's validity. Several studies have developed and used a questionnaire as an additional data collection method next to a driving simulator. Besides, a questionnaire may be used to collect socio-demographic data. With this data it can be checked whether a representative test group is used in driving simulator experiments, and whether driving behaviour is dependent on drivers' characteristics.

3

RESEARCH QUESTIONS AND HYPOTHESES

Based on the background discussed in chapter 2, the research gap is formulated in this chapter in section 3.1. The research gap describes which part of the problem definition is still not answered. In section 3.2, sub research questions and hypotheses are formulated to answer the main research questions from section 1.3.

3.1. RESEARCH GAP

On Dutch motorways there are two types of geometric designs which may be applied at mergers where one lane less is needed downstream of the convergence point, namely the standard geometric design and a merging taper. According to the Dutch design guidelines from the ROA [21] it is preferred to apply the standard geometric design. A merging taper may be applied as an alternative, although this choice must be well motivated. The ROA [21] presumes that a merging taper is unsafe compared to the standard geometric design. However, the underpinning of this presumption is very limited and therefore it is unclear whether the presumption is correct. Besides, if it is assumed that the presumption is correct, it is still unclear how much less safe a merging taper is compared to the standard geometric design. In addition to the Dutch design guidelines, foreign design guidelines neither give clarity on the presumption. The only study [2] about this topic was performed 20 years ago, and did not give a clear picture on the road safety of merging tapers compared to the standard geometric design. It is suspected that merging tapers are less safe compared to the standard geometric design, since merging tapers are prohibited in Germany due to high accident-rates.

The merging taper's design guidelines given in the ROA [21] are neither underpinned, and therefore it is unclear whether these are correct. Therefore, it is unclear what the effect of deviating road designs on road safety is. This is of interest, since a large share of the existing merging tapers on Dutch motorways have a shorter taper-length compared to that recommended by the design guidelines. From literature, it may be expected that several aspects of the road design and traffic conditions influence the driving behaviour and thus road safety at merging tapers. It is suspected that the taper-length, traffic volume and percentage of heavy vehicles affect the road safety on merging tapers, and are further taken into account in this study. Interviews with experts in the field neither gave clarity about the underpinning of the presumption and design guidelines. Decisions in the designing process are based on expert judgement and arguments, and are not based on objective evaluation or scientifically underpinned design guidelines.

3.2. SUB RESEARCH QUESTIONS AND HYPOTHESES

Based on the research gap discussed in section 3.1 and the literature discussed in chapter 2, sub research questions are formulated in order to answer the main research questions stated in chapter 2. From the previous chapters it is now clear which data types may be used in order to measure road safety and which methods are available to do so. Based on that the sub research questions are elaborated. The sub research questions are stated in the same order as the data types are discussed in chapter 2. In addition, the corresponding hypotheses are given based on the background discussed in chapter 2.

As discussed in chapter 2, registered accidents may be analysed to give an assessment on the objective road safety. A high number of accidents on a certain road section indicates that the specific road section is relative unsafe. The number of accidents may be determined on merging tapers with varying values for taper-length, traffic volume and percentage of heavy vehicles. Therefore, the following sub research question is formulated:

1. What is the effect of taper-length, traffic volume and the percentage of heavy vehicles on the number of accidents?

It is expected that on merging tapers with a relative short taper-length, relatively many accidents occur. It is expected that if the traffic volume on merging tapers is relatively high, relatively many accidents would occur. It is expected that if the percentage of heavy vehicles on merging tapers is relative high, relative many accidents occur. As discussed, the number of accidents on merging tapers with varying road design and traffic conditions gives an assessment on the objective road safety on those merging tapers, and a possible assessment on how taper-length, traffic volume and the percentage of heavy vehicles affect objective road safety.

Vehicle trajectories which are measured from driving behaviour may be used in order to calculate surrogate safety measures. With these measurements an assessment can be given on road safety. Surrogate safety measures indicate the conflict-severity on a certain road section. In general, low surrogate safety measures' values indicate a relative unsafe situation. Vehicle trajectories may be obtained from merging tapers with a varying taper-length, traffic volume and percentage of heavy vehicles.

2. What is the effect of taper-length, traffic volume and the percentage of heavy vehicles on the values of different surrogate safety measures?

3. What is the difference in the surrogate safety measures' values on merging tapers compared with the standard geometric design?

It is expected that relatively unsafe values of the surrogate safety measures would result on merging tapers with shorter taper-length / higher traffic volume / higher percentage of heavy vehicles. Besides, vehicle trajectories may also be obtained on the standard geometric design so that surrogate safety measures' values on both road designs can be compared. It is expected that relatively unsafe values of the surrogate safety measures would result on merging tapers compared to values of surrogate safety measures on the standard geometric design, which indicates that merging tapers are unsafe compared to the standard geometric design.

Vehicle trajectories may also be used in order to calculate driving speed and driving speed variation which are also considered as surrogate safety measures. Driving speed can be analysed on both the merging tapers and the standard geometric design. Speeding may be established, which indicates relative unsafe driving behaviour. Braking manoeuvres, which is relative unsafe driving behaviour, may also be obtained from vehicle trajectories. It is expected that relatively many braking manoeuvres take place on merging tapers with a shorter taper-length / higher traffic volume / higher percentage of heavy vehicles. Besides, it is expected that the number of braking manoeuvres is higher on merging tapers compared to the standard geometric design. It is expected that the speed variation is relatively higher on merging tapers with shorter taper-length / higher traffic volume / and higher percentage of heavy vehicles.

Another purpose of vehicle trajectories is to determine the road user's lane selection and lane changing behaviour to give an assessment on objective road safety. The study of Grontmij [2] concludes based on a questionnaire that a large part of road users which approach a merging taper on the right roadway, avoid the tapered lane on purpose because their perception is that this lane is relatively unsafe. By determining the lane selection based on vehicle trajectories, an objective assessment may be given on the lane selection on merging tapers.

4. On which lane do road users driving on the right roadway approach merging tapers?

5. What is the difference in the number of lane changes on merging tapers compared to the standard geometric design?

It is expected that relatively many road users approach the merging taper on the rightmost lane compared to the standard geometric design, because the tapered lane is perceived as unsafe. Relative many lane changes indicate relative unsafe driving behaviour and thus a lower road safety. It is expected that on the standard geometric design fewer lane changes will be performed compared to the number of lane changes on merging tapers. Besides, it is expected that relatively many lane changes occur on merging tapers with shorter taper-length / higher traffic volume / and higher percentage of heavy vehicles.

The opinions and experiences of road users may be used to measure subjective road safety. Road users which have driven on both the standard geometric design and the merging taper, may prefer one of the road designs in terms of their perceived road safety. Instead of measuring the objective road safety at both locations, road users give their opinion about the road safety and share their experiences on both road designs.

6. What is the perceived road safety on merging tapers compared to the standard geometric design?

It is expected that road users perceive a merging taper as less safe than the standard geometric design. This hypothesis is based on informal conversations with friends, colleagues and fellow students.

The next chapter describes which methods are used in order to answer the research questions and check whether the hypotheses from this chapter are correct.

4

RESEARCH METHOD

This chapter discusses the methods which are used in order to answer the research questions. Section 4.1 explains which methods are chosen and why this is done. The method selection was done based on the literature which is discussed in chapter 2, and the hypotheses which are discussed in chapter 3. The up-following sections explain the methods in more depth, and how the methods are used to answer the research questions in this thesis.

4.1. METHOD SELECTION

Chapter 2 discussed several methods which may be used to measure road safety. Based on that chapter, a research method was developed which is displayed in the flowchart in figure 4.1. With the registered accidents, an accident analysis was conducted with accidents which are registered between 2010 and 2013. Vehicle trajectories were collected in a driving simulator experiment, in order to measure driving behaviour and make an assessment on road safety. The opinions and experiences of road users were collected in a questionnaire which is conducted prior to the driving simulator study. The selection of these three methods is shortly explained in this section, after which the methods itself are explained in more detail in the up-following sections.

Of the three selected methods, **accident data analysis** is the most convenient. This method was used in the exploring phase of this research in order to get a broad overview on accidents which occurred at merging tapers. Based on literature, it was expected that the quality of the accident data is not sufficient. However, accident data analysis was used in this study to get a first insight in the "objective" road safety on merging tapers.

Next to the accident analysis, a **driving simulator study** was performed to measure driving behaviour using vehicle trajectories. Advantages of collecting vehicle trajectories in a driving simulator are for example freedom in designing the experiment, participant's safety and straightforward data collection. An assessment of road safety was given using surrogate safety measures which were calculated from the vehicle trajectories. Road safety of both the standard geometric design and merging tapers was assessed using surrogate safety measures, in order to check the presumption that a merging taper is unsafe compared to the standard geometric design. Driving behaviour on merging tapers with varying traffic conditions and road design was measured in order to assess road safety as a result of the varying factors. As discussed in the previous chapter, the factors taper-length, traffic volume on the left roadway, traffic volume on the right roadway and percentage of heavy vehicles were taken into account.

A **questionnaire** is conducted prior to the driving simulator experiment to measure subjective road safety on both merging tapers and the standard geometric design. In the questionnaire, participants could give their opinion about the road safety on both road designs. From that, the subjective road safety of merging tapers compared to the standard geometric design was determined.

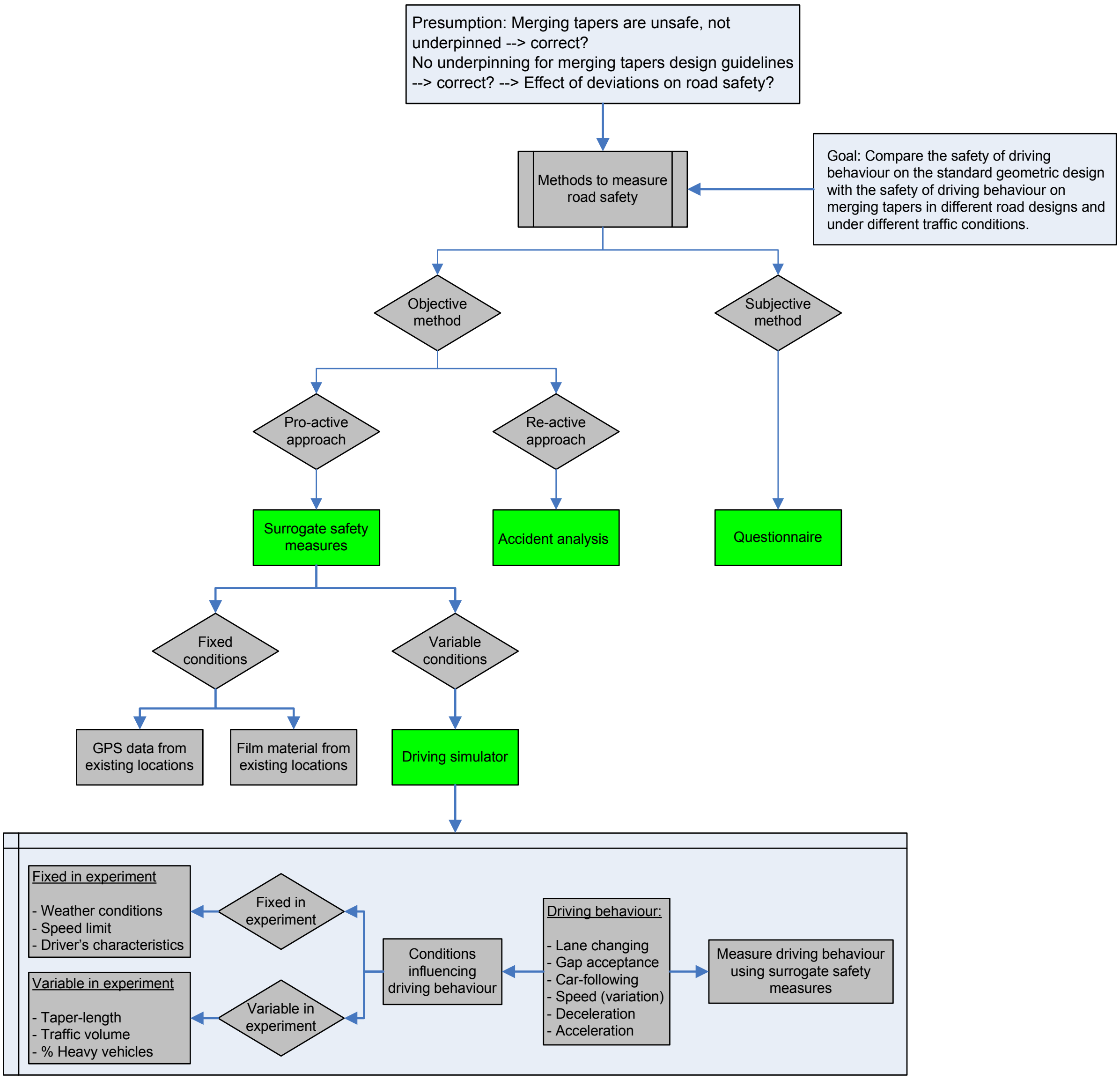


Figure 4.1: Flowchart of the method selection in this study.

4.2. ACCIDENT DATA ANALYSIS

This section explains how historical (2010 to 2013) accident data was analysed in this study in order to measure road safety. First it is explained from which locations the accident data is collected, and why these locations are chosen. Then it is explained from which source the accident data was retrieved, which accident registrations were taken into account, and how the data analysis was performed.

4.2.1. DATA COLLECTION

Accident data was collected from mergers on Dutch motorways, in both the merging taper design and the standard geometric design. An as complete as possible list of merger locations was made in collaboration with experts in the field. From this list, a selection of representative locations was derived. In this study, a representative location was characterized by its geometric design and the road environment around the merger. The following aspects were taken into account when selecting such a representative location:

- **Discontinuities upstream and downstream of the merger.** Discontinuities are convergence points and divergence points which influence driving behaviour on for example a merger. A discontinuity influenced the driving behaviour at a merger, if the discontinuity is located too close to the merger. Since driving behaviour affects road safety, the presence of a discontinuity may have influenced the accident data. Therefore, a minimum distance upstream and downstream of the merger was maintained. The *turbulence length* was used as a threshold value, since this distance is defined as follows by the NOA [4]: "turbulence distances are distances at convergence and divergence points over which the driving behaviour and traffic flow is being influenced as a result of the convergence and divergence points"

- **Unexpected objects in the environment.** For example remarkable buildings and special attractions might influence driving behaviour, and thus might have influenced road safety and accident data. Presence of such objects was checked with the usage of Google street view.
- **Other unexpected geometric design upstream or downstream the merger.** For example small radii, peak lanes and weaving sections too close to the merger location might influence the driving behaviour, and thus might have influenced road safety and accident data. Presence of such unexpected geometric designs was checked by the usage of Google street view.

A 2+2 lane configuration is the most common configuration of merging tapers on Dutch motorways. Therefore only 2+2 configured mergers were taken into account in this thesis. The selected representative merging taper locations are listed in table 4.1. The selected representative merger locations with the standard geometric design are listed in table 4.2.

Table 4.1: Representative merging taper locations which were used for the accident data analysis, including their exact location, taper-length and speed limit (06:00-19:00).

Number	Name	Location	Taper-length [m]	Speed limit [km/h]
1	Eemnes	A1-Li 28,2	100	100
2	Coenplein	A10-Re 32,0	125	100
3	Waterberg	A12-Li 127,3	200	120
4	Grijsoord	A12-Re 121,5	230	120
5	Prins Clausplein	A12-Re 7,7	125	100
6	Galder	A16-Li 67,0	200	120
7	Eemnes 2	A27-Li 97,3	215	120
8	De Baars	A58-Re 36,6	200	130

Table 4.2: Representative merger locations with the standard geometric design, which were used for the accident data analysis, including their exact location, length (point of the gore - end lane drop) and speed limit (06:00-19:00).

Number	Name	Location	Length [m]	Speed limit [km/h]
1	Leidschendam	A2-Li 43,3	1120	100
2	Holendrecht	A9-Re 23,2	910	100
3	Ypenburg	A4-Re 47,7	920	100

Accident data which was used in the analysis was retrieved from the *Bestand geRegistreerde Ongevallen Nederland (BRON)* [22], which stands for *Dutch registered accidents file*. In this file, police accident reports are linked to the *Nationale Wegenbestand (NWB)*, the National Road file in which all Dutch roads are registered. Accidents in this file should be documented including location, severity, nature of the accident, and possible injuries and fatalities. The data is owned and managed by Rijkswaterstaat, and is publicly accessible.

Registered accidents in BRON [22] are registered including the road section number, which are linked to the corresponding national motorway numbers. Also the driving direction and hectometre sign is registered, with which the accident's location was determined. However, the location's accuracy is low. Only one hectometre sign is registered per accident, and as a result a specific accident might have occurred 100 metres upstream or 100 metres downstream of the registered hectometre sign. This resulted in an error of the accident's location of 200 metres.

Driving behaviour prior to the accident must not be influenced by the geometric design other than the merger present upstream or downstream of the accident location. Therefore, boundaries were set upstream and downstream of the accident location in which accidents were taken into account. In the analysis, the boundaries were set according to the turbulence distance which is stated in the ROA [21]. The turbulence distance is defined as follows: "turbulence distances are distances at convergence points and divergence points over which the road user behaviour and traffic flow is being influenced as a result of the convergence and divergence points". Turbulence is characterized by deviations in headway, distribution of the vehicles over the lanes, braking, evasive actions and lane changing. By solely taking into account accidents which occurred within the stated boundaries, it is sure that the driving behaviour prior to the accident was not influenced by the turbulence caused by discontinuities other than the merger itself.

The turbulence length was determined by the design speed and the type of discontinuity (e.g. merger, insertion, splitting or exit). The ROA [21] states that the turbulence length upstream of the point of the gore is 150 m, and downstream of the taper-point the turbulence length is 375 m assuming a design speed of 120 km/h (see figure 4.2). Regarding a design speed of 90 km/h, the turbulence length upstream of the gore is 120 m and downstream of the taper-point the turbulence distance is 300 m. Using these boundaries, accident data was analysed at the selected locations. The boundary distances at each location can be seen in table 4.3, and were measured from the point of the gore. The boundary distance downstream of the point of the gore may be variable despite of a constant design speed, since the taper-length is variable. The speed limit on the selected mergers with the standard geometric design is the same on all locations. As a result, the boundaries in which accidents were collected for these locations are the same for each location. Upstream of the point of the gore 110 m was taken into account, and downstream of the end of the lane drop also 110 m was taken into account.

Table 4.3: Boundary distances upstream and downstream of the point of the gore of the representative merging tapers, used to select the relevant accident data.

Merging taper number	Distance upstream of point of the gore [m]	Distance downstream of point of the gore [m]
1	120	400
2	120	425
3	150	625
4	150	615
5	120	425
6	150	575
7	150	590
8	150	575

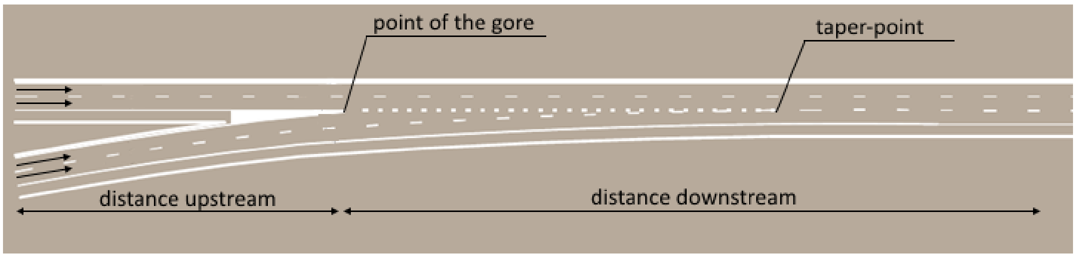


Figure 4.2: Schematic representation of a merging taper indicating the location of the point of the gore, taper-point and boundary distances upstream and downstream of the point of the gore.

4.2.2. DATA ANALYSIS

The relevant accident data was analysed using Excel. It was tested whether there exists a correlation between taper-length and the number/severity of accidents. For example, a merging taper with a short taper-length and high number of accidents may indicate that a short taper-length has a negative effect on road safety. Also the distribution of accidents over time was determined, to find a correlation between the number of accidents and traffic volume. Besides, the quality of the accident data was studied by comparing accident data over the years and reviewing literature.

4.3. DRIVING SIMULATOR EXPERIMENT

This section discusses the driving simulator and the driving simulator experiment. First, it is explained which hardware and software was used in the driving simulator. Then it is explained how the 3D environment for the experiment was built. Several aspects of the driving simulator were adjusted in order to make it as realistic as possible, which is discussed in the up-following section. Then it is discussed how data was collected from the driving simulator and how the data was analysed. In the last part of this section, the experimental design of the driving simulator experiment is discussed.

4.3.1. HARDWARE

In order to create an as realistic as possible driving simulator vehicle, the hardware of the driving simulator's vehicle was chosen carefully. The aim of choosing the right hardware components was to create the feeling of driving in a real life vehicle. The hardware can be seen in figure 4.4 and figure 4.3.

A vehicle seat of the brand *Playseat* was used in the driving simulator. This vehicle seat is intentionally designed for gaming purposes, but it gives the perception of a real-life vehicle seat. The construction of the seat makes it possible to attach a steering wheel and pedals. A steering wheel and pedals of the brand *Logitech* are used in the driving simulator. The pedals and steering wheel were mounted on the construction of the vehicle seat. As a result, the essential vehicle-control parts were located at a similar location as in a real-life vehicle. The force feedback parameters which determine the steering wheel's resistance, were calibrated by comparing the driving simulator's steering resistance with the resistance of a real-life's steering resistance. A PC was used to run the required software programs in order to perform the experiment. The road environment and vehicle's design which normally can be seen in a vehicle, was shown on the screen in a 3D environment. Besides, the screen was used in order to manage the experiment.

Figure 4.3: Driving simulator's hardware: vehicle seat, steering wheel and pedals.

Figure 4.4: A participant driving in the driving simulator during the experiment.

4.3.2. VISSIM

The remaining traffic in the driving simulator experiment was generated by the microscopic traffic simulation program VISSIM. This subsection explains how VISSIM was used in the driving simulator experiment. The merging taper design is discussed, as well as the generation of vehicles and driving behaviour of the simulated vehicles.

Merging taper design Motorways in VISSIM were constructed with *links*, which were connected to each other using *connectors*. The number of lanes and the lane-width were defined for each separate link. All motorways (links and connectors) together created a network on which vehicles drove from an origin to a destination. The traffic volume was predefined as well as the origin and destination of the vehicles. A merging taper design in VISSIM (see figure 4.5) consisted of 3 links and 2 connectors. Participants approached the merging taper on a 2-lane roadway which is built with a *link*. The tapered road segment was constructed by two 2-lane overlapping *connectors*, which is illustrated in figure 4.5 by the red surface. At the downstream-end of the overlapping connectors, a 3-lane link is built on which the vehicles continue downstream of the merging taper.

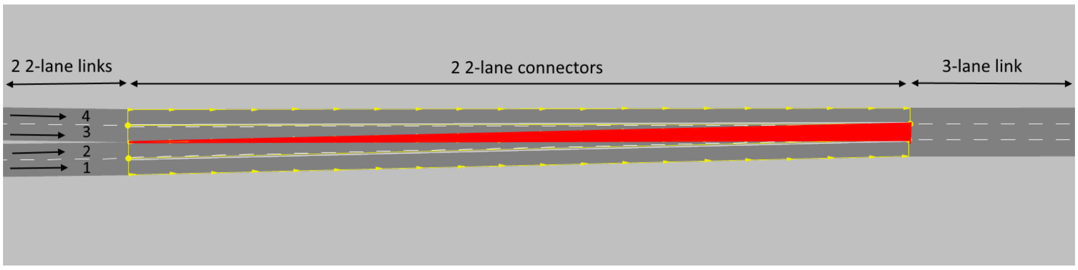


Figure 4.5: The design of a merging taper in VISSIM, using links and connectors.

As explained above, two connectors overlapped in the tapered road segment. Vehicles which are located on the same link or connector in VISSIM, notice each other and behave following the driving behaviour models which are integrated in VISSIM. However, vehicles on different links or connectors do not notice each other, which holds that vehicles on a merging taper are able to drive through each other without noticing. In order to prevent this, so-called "conflict areas" were used on the overlapping lanes. A conflict area is illustrated in figure 4.6 by the green and red surface. On Dutch motorways, inserting traffic may not disturb through traffic. Therefore, in VISSIM it was set that traffic on the red surface prioritises traffic on the green surface. This means that vehicles on the red surface must search for an acceptable gap on the green surface or the most right lane (lane 1 in figure 4.5). The VISSIM manual [20] states that the attributes of a conflict area influence the driving behaviour of any vehicle approaching the conflict area. This is why vehicles may change its intention, and thus its driving behaviour in a particular traffic situation.

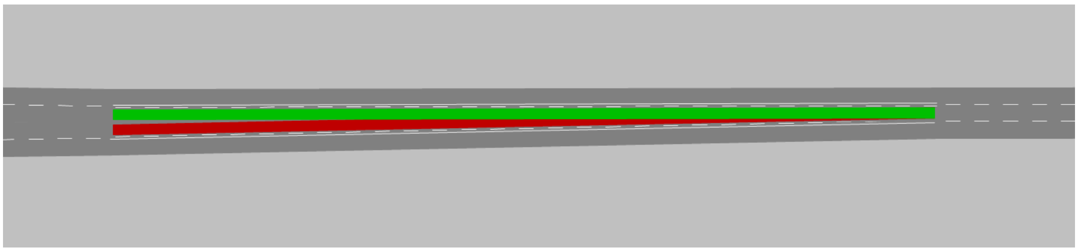


Figure 4.6: Conflict areas on overlapping connectors in VISSIM. Traffic on the red surface prioritises traffic on the green surface.

Many parameters of the conflict area may be adjusted, with which the driving behaviour of the approaching vehicles is influenced. Each parameter is explained, and the final values are given in table 4.4. Calibration was done by using *face validity*, which holds that the driving behaviour of the simulated vehicles on the merging taper looked realistic. In the calibration process, an iteration process was performed to determine the parameters. Parameters were adjusted until realistic driving behaviour on the merging taper was observed. The following *measures of effectiveness* were taken into account when identifying realistic driving behaviour:

- No vehicles driving through each other.
- No abrupt accelerating/decelerating.
- A realistic headway for merging traffic.

Table 4.4: Conflict area's parameters of the VISSIM simulation, used in the driving simulator experiment.

Parameter	Explanation	Value
VisibLink1	Maximum distance at which an approaching vehicle can "see" the vehicles on the other link	100 m
VisibLink2	Maximum distance at which an approaching vehicle can "see" the vehicles on the other link	100 m
FrontGapDef	Time that a yielding vehicle waits before it also enters the conflict area, after the vehicle with the right of way has entered it	1,5 s
RearGapDef	This setting only holds for crossing conflicts, not for merging conflicts	0,5 s
SafDistFactDef	This factor is multiplied with the normal desired safety distance of a vehicle in the main traffic stream in order to determine the minimum distance a vehicle of the yielding traffic stream must keep when it is completely in the conflict area. Assuming a smaller SafDistFactDef means that merging vehicles may merge on a relative small distance in front of the vehicle in the main traffic stream. The desired safety distance is defined in the car following model as the minimum distance a driver will maintain while following another vehicle. It is calculated by multiplying the standstill distance with the headway time and the speed. The standstill distance is the CC0 parameter from the Wiedemann 99 model, and the headway time is the CC1 parameter from the Wiedemann 99 model.	2,5 [-]
AddStopDist	This parameter is only relevant for vehicles that have to yield. It gives the distance that moves the (imaginary) stop line upstream of the conflict area. As a result, yielding vehicles stop further away from the conflict	0 m
ObsAdjLns	If this option is selected, incoming vehicles of the main traffic stream that are required to yield will account for the vehicles in the main traffic stream that want to change to the conflicting lane	-
AnticipRout	Percentage of vehicles required to yield that account for the routes of vehicles with the right of way. These are approaching with the main traffic stream and will turn further upstream. They will thus not reach the conflict area.	0 %
AvoidBlock	Not relevant if AnticipRout is 0	-

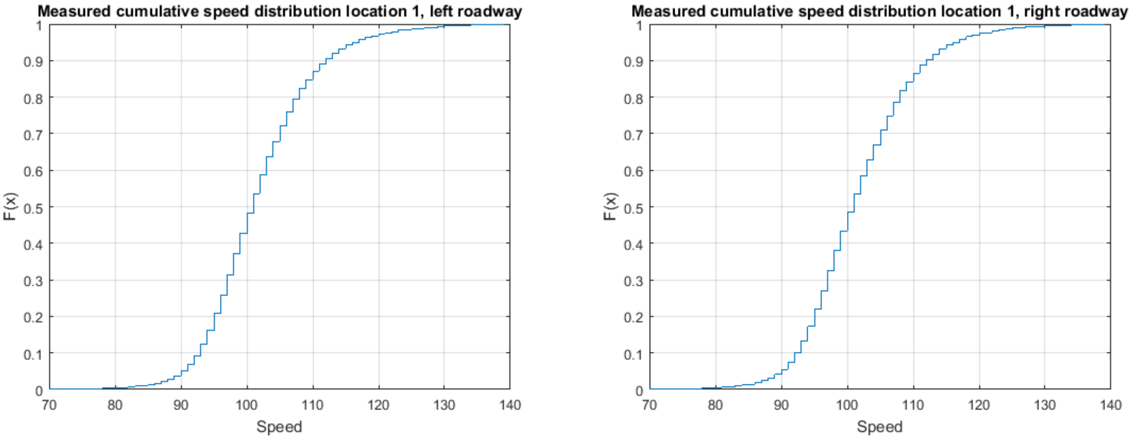
Generating vehicles Vehicles in VISSIM were generated by so-called *vehicle inputs*. One vehicle input was present on each link which generates all vehicles at that origin. A vehicle was placed on the lane with the largest headway. Vehicle inputs generate vehicles which follow a static route, which means that the route is determined for each vehicle directly after the vehicle is generated. The traffic volume can be defined for every possible time interval, for example 15 minutes or 30 minutes. Each time interval has its own "volume type", which can be either *stochastic* or *exact*. In this study, the volume type *exact* was chosen, which means that the vehicle input generated exactly the specified number of vehicles.

The vehicles from the vehicle inputs were generated over time according to a Poisson distribution [75]. The Poisson distribution is the oldest and most widely used traffic model in practice. The number of departures in a given time interval [0,t] follows the Poisson distribution with mean λt. The time gap x between two successive vehicles follows the exponential distribution with the mean $1/\lambda$. λ is measured in vehicles per hour. The probability of a time gap x between to successively generated vehicles can be determined using the following equation:

$$f(x,\lambda) = \lambda e^{-\lambda x} \tag{4.1}$$

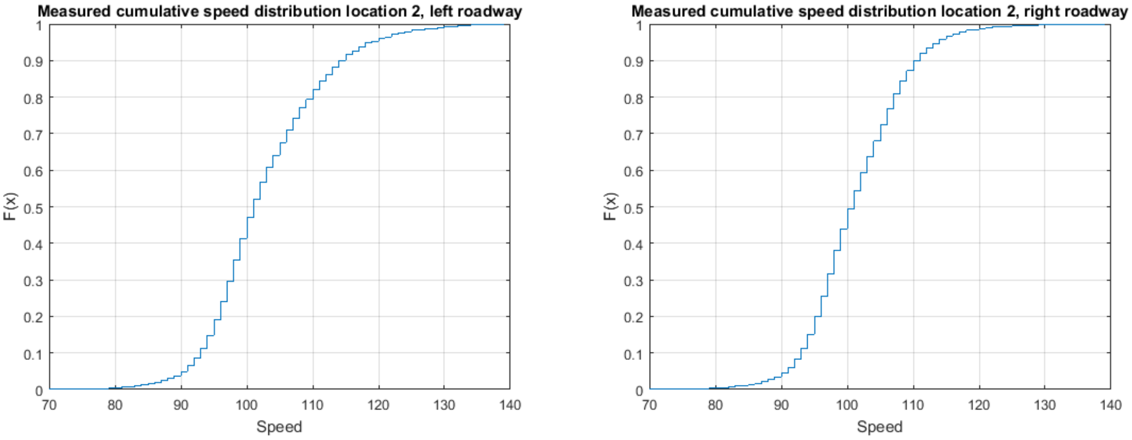
Driving behaviour Each simulated vehicle in VISSIM has assigned a driving behaviour which contains of many factors. As participant's driving behaviour is influenced by the driving behaviour of the simulated traffic, the realism of the simulated vehicle's driving behaviour must be as good as possible. Simulated vehicle's driving behaviour is based on models, and therefore based on assumptions. The driving behaviour of the simulated vehicles is therefore not completely realistic. Prior to the driving simulator experiment, several parameters of VISSIM's driving behaviour were adjusted in order to improve the realism of the simulated vehicle's driving behaviour. This paragraph discusses the behavioural models, the parameters which are adjusted, and the data which is used for this.

Each vehicle has a desired speed which is aimed to be maintained during the complete simulation time. The desired speed of each vehicle is determined from the *desired speed distribution*, which are predefined distributions in VISSIM. In order to make the desired speed distribution in VISSIM as realistic as possible, an empirical speed distribution is imported. Empirical speed measurements were collected from loop detectors of the NDW [19] located at merging taper locations 1 and 2 (see table 4.1) which have a speed limit of 100 km/h. At the loop detectors, the speed of each passing vehicle was measured for a period of one year. The empirical cumulative speed distribution of the left and right roadway of both merging taper locations are plotted in figure 4.7. The empirical cumulative speed distribution in figure 4.7 was imported in VISSIM, and was used as the desired speed distribution for simulated vehicles in the driving simulator experiment.



(a) Cumulative speed distribution on location 1, left roadway.

(b) Cumulative speed distribution on location 1, right roadway.



(c) Cumulative speed distribution on location 2, left roadway.

(d) Cumulative speed distribution on location 2, right roadway.

Figure 4.7: Cumulative speed distribution on merging taper locations 1 and 2, derived from loop detector data of the NDW. [19]

The driving behaviour which is simulated in VISSIM is based on driving behaviour models. Regarding car-following behaviour, two Wiedemann models are implemented in VISSIM. The Wiedemann car-following models are psycho-physical models for longitudinal vehicle movements. The model is called a psycho-physical car-following model since the model accounts for psychological aspects as well as for physiological restrictions of drivers' perception. The models are based on Wiedemann's research work, which assumes that there are basically four different driving states for a driver [20]:

- *Free driving.* No influence of preceding vehicles can be observed. In this state, the driver seeks to reach and maintain his desired speed. In reality, the speed in free driving will vary due to imperfect throttle control, but it will always oscillate around the desired speed.

- *Approaching.* Process of the driver adapting his speed to the lower speed of a preceding vehicle. While approaching, the driver decelerates, so that there is no difference in speed once he reaches the desired safety distance.

- *Following.* The driver follows the preceding car without consciously decelerating or accelerating. He keeps the safety distance more or less constant. However, again due to imperfect throttle control, the difference in speed oscillates around zero.

- *Braking.* Driver applies medium to high deceleration rates if the distance to the preceding vehicle falls below the desired safety distance. This may happen if the driver of the preceding vehicle brakes abruptly or the driver of a third vehicle changes lane in order to squeeze in between two vehicles.

Drivers switch from one state to another as soon as they reach a certain threshold that can be described as a function of speed difference and distance (see figure 4.8).

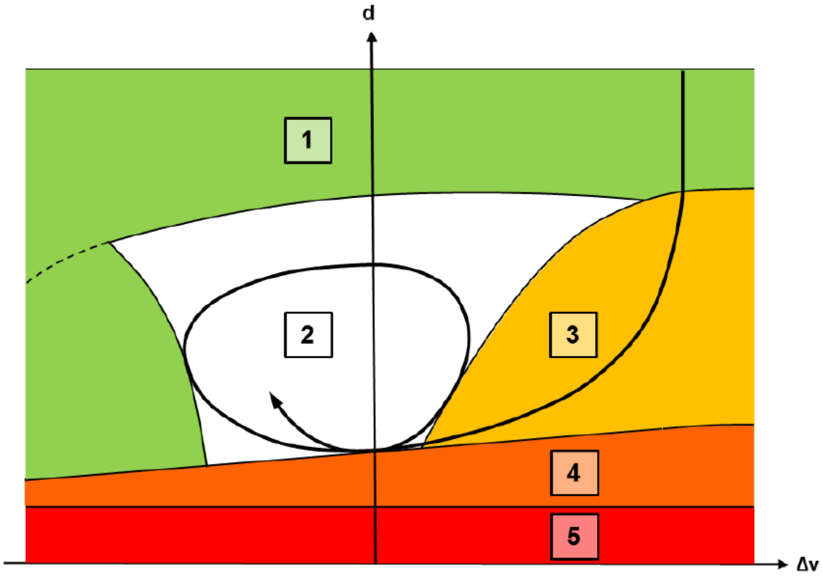


Figure 4.8: Car following model according to Wiedemann. [20]

Next to the car-following model, lane change behaviour may be determined in VISSIM. The lane change settings in VISSIM consist of general lane change behaviour and parameters which describe the driving behaviour in more detail. The general lane change behaviour is set to *slow lane rule* in which rules are implemented following the StVO (German Traffic Code). These rules indicate that overtaking is solely permitted on the left side, which is similar to the Dutch traffic regulations and is therefore realistic.

VISSIM distinguishes the following types of lane changing [20]:

- *Necessary lane change.* Lane changes needed to follow the predefined route.
- *Free lane change.* Lane changes made if there is more space and a higher speed is required.

For both lane change types mentioned above, vehicles need to find a suitable gap in the driving direction. Which gap size is accepted depends on two speeds, namely the speed of the lane-changing vehicle and the speed of the vehicle approaching on the adjacent lane. For necessary lane changes, the time gap also depends on drivers' "aggressiveness" which is based on the driving behaviour parameters.

Both car-following model as the lane change model are models which are based on assumptions which are made not very recently based on German driving behaviour. In order to create as realistic possible driving behaviour in the driving simulator experiment, the driving behaviour models were calibrated. Geometric design, traffic composition and driver's characteristics influence the driving behaviour, and therefore a unique driving behaviour model may be determined for each unique situation. Since the experimental road in this study is a fictive road, it was impossible to perfectly calibrate the driving behaviour models using data from similar real-life locations. However, the car-following behaviour and lane change behaviour was calibrated in several studies, of which the calibration performed by Oud [76] was regarded as the most elaborated of all found calibration studies. Empirical vehicle trajectories from the A270 nearby Eindhoven were used to calibrate the driving behaviour models in VISSIM. Measures of effectiveness which were used in the calibration process are frequency of lane changes, accepted gap distribution, space distribution of merging lane changes and acceleration of vehicles influenced by the lane changes. Oud [76] concluded that the parameters *Headway Time, To slower lane if collision time is above* and *Safety distance reduction factor* have the most significant effect on the goodness of fit. An iteration was performed from which the most realistic values for these parameters were determined. The values which gave the most realistic driving behaviour were implemented in VISSIM. The values were set to 1,50 for the *Headway Time*, 40,00 for *To slower lane if collision time is above*, and 0,95 for the *Safety distance reduction factor*.

Next to car-following and lane changing behaviour, also lateral behaviour may be set in VISSIM. By default, simulated vehicles in free flow drive exactly in the middle of a lane. However, real-life vehicles do not constantly drive in the middle of the lane due to imperfect steering of road users. In order to make lateral driving behaviour more realistic, the desired lateral position for vehicles in free flow was set to *any* which holds that vehicles may drive on the left side, right side or middle of the lane.

4.3.3. DEVELOPING THE 3D ENVIRONMENT

Software programs AutoCAD, Civil3D, 3Ds Max and Unity were used to develop the 3D environment used in the driving simulator experiment. First, AutoCAD was used to design the 2D geometric design of the motorway which was used in the experiment. Second, Civil3D was used in order to add the 3D components such as road signs, guide rails and road marks to the 2D model. A *surface* was created which is based on the asphalt surface designed in AutoCAD. The finished 3D model was imported in 3Ds Max, in which the created surface was made solid. Without creating a solid surface, the vehicles in the driving simulator experiment would drop through the asphalt surface due to gravity. The exported models from 3Ds Max were suitable for importing into Unity.

Unity is a game development platform, in which high quality 3D and 2D games can be developed. Unity combines the 3D environment, the VISSIM model, scripts and the driving simulators' vehicle to one executable which may be runned on the computer. Export files from 3Ds Max with the geometric road design and objects in the environment are imported in Unity. Colours and materials of for example asphalt, guide rails, vehicles and sky can be determined in Unity, as well as the printing of the road signs. Sunlight is also determined and simulated in Unity, as if it is at the middle of the day.

The driving simulator vehicle's characteristics and communication with the VISSIM simulation was provided in several scripts which were added in the final executable. The scripts ensured that one of the vehicles in VISSIM was assigned to the driving simulator's vehicle, and that this vehicle communicated with the remaining vehicles in the simulation. Vehicle's characteristics defined in the scripts were calibrated in order to make the vehicle's characteristics as realistic as possible. For example power, torque and steering parameters were adjusted iteratively using face validity, so until they match vehicle's characteristics which are observed in a real-life vehicle.

4.3.4. DRIVING SIMULATOR DEVELOPMENT

The driving simulator was constantly developing in the run up to the experiment. Experts of Witteveen+Bos and myself made adjustments to the driving simulator in order to improve the realism of the driving simulator. Factors such as the vehicle's characteristics, environmental lay-out and realism of the simulated vehicles influence the participants' driving behaviour and thus road safety. The driving behaviour performed in the driving simulator must be as similar as possible to driving behaviour performed in real-life. During the driving simulator development, many people have driven in the driving simulator for their first time and provided feedback on the realism of the driving simulator. Based on their feedback and my own feedback, several improvements were introduced:

- More direct reaction on steering and acceleration/deceleration.
- Flashing lights were implemented on all simulated vehicles.
- Vehicle windows were made see-through, so that preceding vehicles were better visible.
- A speedometer, rev counter and gear-indicator were implemented in order to increase the sense of speed.
- Acceleration and deceleration parameters were adjusted in order to make the vehicle's characteristics similar to a real-life vehicle, which was validated using face validity.
- Parameters for steering sensitivity were adjusted, which was also validated using face validity.
- The possibility to switch between automatic shifting and gear-shifted driving was implemented. In this experiment, solely automatic shifting was used in order to increase the controllability of the vehicle.

4.3.5. EXPERIMENTAL DESIGN

This subsection discusses the experimental design of the driving simulator experiment. It is explained which components are present in the experiment, which are discussed in more depth later in this subsection. In general, the aim was to keep the complete experiment as short as possible, for the following reasons:

- Participants will get tired during the experiment. By limiting the duration of the experiment, fatigue will have relatively less influence on the results. The same holds for the participant's concentration.
- Simulator sickness can be limited by keeping the experiment relative short [63]. By limiting the duration of the experiment, less participants might become sick.
- If the experiment takes relative short, more people are willing to participate.

Components of the experiment The experiment consisted of six components which can be seen in table 4.5. Each component is discussed in the paragraphs below.

Table 4.5: Duration of each component of the driving simulator experiment.

Component	**Duration [min]**
1. Introduction	5
2. First part questionnaire	5
3. Practice driving simulator	15
4. Driving simulator experiment	15
5. Second part questionnaire	10
6. Buffer	10
Total	**60**

The complete experiment was explained to the participants in the introduction component (see appendix E). It was explained what was expected of the participant in each component of the experiment, and what the duration of each component was. After the participant indicated that he/she understands the instructions, the first part of the questionnaire was performed. Questions were asked about the participant's familiarity and perception of safety of a merging taper and the standard geometric design. Also socio-demographic data was collected such as age, gender and driving experience. The questionnaire is discussed in more depth in section 2.3.4.

After the first part of the questionnaire was finished, participants practised in the driving simulator. None of the participants had driven in this driving simulator before. Therefore, participants were allowed to practise for 15 minutes in order to get used to the characteristics of the driving simulator and the simulated environment. At the end of the practise session it was assumed that participants had a good control over the driving simulator, so that their performed driving behaviour is as much as possible similar to real-life driving behaviour. During the development of the driving simulator, many people had driven in the driving simulator for their first time. They indicated that the controllability of the driving simulator improves the most in the first 5 minutes of practising. A duration of 15 minutes for practising was chosen, which is a compromise between keeping the experiment reasonably short and to be more certain that participants showed realistic driving behaviour. After the participants practised in the driving simulator, the final driving simulator experiment was performed. All participants drove over a predefined route on a motorway, on which different merger designs were present. The design of the predefined route is discussed in more depth later in this subsection. The participants were asked to drive through the simulated environment in the same manner as they do in real-life, which holds that participants drove following the traffic regulations.

The second part of the questionnaire was performed after the driving simulator experiment. Questions were focussed on perception of realism in the driving simulator, and the perception of control in the driving simulator. Also a blanco textbox was added so that participants could give general comments about the driving simulator experiment. A time buffer was added in the experiment in order to prevent delay in the participant's schedule. Delay may have been caused by participants which are too late or if the driving simulator shows difficulties. For example, the driving simulator software crashed sometimes due to teething troubles which could not be fixed prior to the driving simulator experiment. Delay which may be caused by this, is prevented by adding a buffer to the experiment.

Experimental road design The experimental road design is defined as the complete predefined route which the participants must complete. The experimental road design consisted of several scenarios, which were mergers including a longitudinal distance upstream and downstream over which data is collected (see table 4.10). A schematic overview of a part of the experimental road can be seen in figure 4.9, in which each blue rectangle represents a merger. Each number represents an origin or a destination. Participants entered the experiment at origin number two, and continued their predefined route over each scenario. At an origin or destination, simulated vehicles entered or left the experiment so that the traffic volume was regulated on each scenario. In total, nine different scenarios were designed of which one had the standard geometric design and eight had a merging taper design with varying factors (taper-length, traffic volume and percentage of heavy vehicles). The factor's level in each scenario was either high or low (see table 4.7), in order to measure the effect of these factors on driving behaviour.

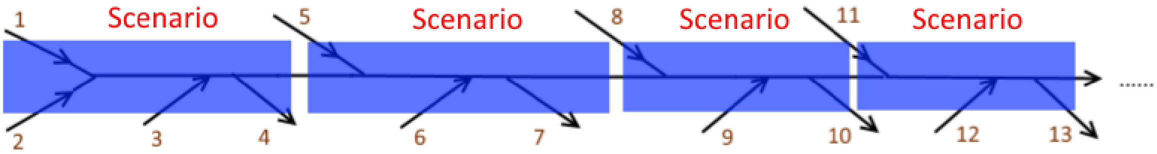


Figure 4.9: Schematic representation of a part of the experimental road design, including scenarios, on-ramps and off-ramps.

When all high and low level factors would be combined in an experimental design, a full factorial design must have been created which results in $2^4 = 16$ unique merging taper scenarios. After including a scenario with the standard geometric design, a total of 17 unique scenarios must be completed by the participants. Assuming the geometric design from appendix B, and assuming an average speed of 100 km/h, one scenario was expected to be completed in around 90 seconds. Completing all 17 scenarios in the experiment would result in a total duration of 25,5 minutes. Since the aim was to keep the experiment's duration as short as possible, a so-called *fractional factorial design* was used as the experimental design [**?**]. With this method, it was possible to lower the number of scenarios and thus lower the experiment's duration. In the *fractional factorial design*, factor X1 was defined as the taper-length or the length to the lane drop, X2 was the traffic volume on the left roadway, X3 was the traffic volume on the right roadway and X4 was the percentage of heavy vehicles.

Fractional factorial design made it possible to lower the number of scenarios to 8 (2^{4-1}). Of four of the factors mentioned above, one factor (X4) was confounded with the interaction of the three main factors (X1, X2 and X3). Based on the literature study it was expected that the percentage of heavy vehicles have the least effect on the driving behaviour on mergers. Therefore, in the fractional factorial design, X4 was confounded with the interaction between X1, X2 and X3. The factor's level on each scenario can be seen in table 4.6. A plus-sign indicates a high level value, and a minus-sign indicates a low level value. It can be seen that for the main factors X1, X2 and X3, all unique combinations of levels were made. As a result of the confounding, the level of X4 was determined by the multiplication of the other factor's level in that scenario.

In addition to the eight merging taper scenarios with varying values, a scenario was added with the standard geometric design. The standard geometric design in this experiment was designed according the guidelines of the ROA [21]. The values for traffic volume and % of heavy vehicles were averages of the factor's values in the other scenarios. With the chosen values it was expected that the driving behaviour on merging tapers and the standard geometric design can be compared fairly.

Table 4.6: Experimental design of scenarios, using fractional factorial design.

Scenario	High level factors	X1	X2	X3	X4 (=X1*X2*X3)
S1	(1)	-	-	-	-
S2	x1	+	-	-	+
S3	x2	-	+	-	+
S4	x1x2	+	+	-	-
S5	x3	-	-	+	+
S6	x1x3	+	-	+	-
S7	x2x3	-	+	+	-
S8	x1x2x3	+	+	+	+
S9	N.A.	Guidelines	Average	Average	Average

In order to determine the factor's values, it was first decided in which range the low and high factors are chosen. The value's range can be seen in table 4.7, and is discussed below the table. In this range, the factor's values are chosen from a uniform distribution with the range as boundaries. In between the low and high values' uniform distribution, a gap was assumed in order to make a clear distinction between low and high values. The factor's values which were chosen in the driving simulator experiment are given in table 4.8, and are explained in more depth below.

Table 4.7: Low values' range and high values' range from which the factor's values were chosen for the driving simulator experiment.

Factor	Low values' range	High values' range
Taper-length [m]	100-160	190-250
Traffic flow [veh/h]	1800-2100	2300-3000
Percentage of heavy vehicles	0 (fixed value)	20 (fixed value)

Values for the taper-length were derived from existing merging taper locations (see table 4.1), and varied between 100 m and 250 m. Guidelines from the ROA [21] solely prescribe taper-lenghts longer than 170 m. However, since on Dutch motorways several too short merging tapers are located, it was found interesting to study relative short merging tapers as well. Therefore, values for low levels were chosen between 100 m and 160 m, and values for high levels were chosen between 190 m and 250 m. In the real-life designing process, it is usual to round up the taper-length to dozens. Therefore, values for the taper-length were chosen by hand and were then randomly divided over the scenarios. The final design of the scenarios can be seen in table 4.8.

Values for the traffic flow were chosen based on the following:

- In the accident data analysis from chapter 5, it is suspected that the number of accidents on merging tapers was affected by the traffic flow. Therefore, it was found interesting to take into account decisive traffic flows from these locations. Plots of the average working days' traffic flow are shown in appendix A. Traffic flow peaks varied between 1800 veh/h and 2200 veh/h on the one roadway, and between 2000 veh/h and 3000 veh/h on the other roadway.
- Guidelines from the previous design guidelines in the NOA [4] prescribe maximum V/C-ratios upstream of the merger, which should be lower than 0,8. In the new ROA [21], this value has been lowered to 0,7. The ROA states that none of both roadways should have a V/C-ratio higher than 0,7. Therefore, it was found interesting to study traffic volumes which are in the range of this V/C-ratio.

Taking into account the measured traffic volumes and the guidelines from the ROA, a maximum traffic flow of 3000 veh/h was chosen. Based on the empirical traffic flow data, 1800 veh/h was chosen as a lower limit. Downstream of the convergence point, one lane less is available. Therefore, the sum of the two traffic volumes may not exceed the motorway capacity until which the traffic will flow good according to the CIA [77]. The CIA prescribes a maximum V/C-ratio of 0,8, and thus the traffic flow may not exceed 0,8*6300 = 5040 veh/hour. In some scenarios, the traffic flow on the left and right roadway will have both a value which is chosen from the high range, which sometimes results in a too high V/C-ratio downstream of the merger. In order to meet the requirement of 5040 veh/h downstream of the merger, the threshold between low range and high range was shift towards the low range. Low values were chosen in the range of 1800 to

2100 veh/h, and high values in the range of 2300 to 3000 veh/h. Values were randomly chosen using the Latin Hypercube Sampling method. This method divided the range in subranges, and chose random values from these subranges. Using this method the values were randomly chosen, but also reasonably distributed over the range defined in table 4.7. At the standard geometric design, an average traffic volume was chosen.

On some of the loop detector locations of the NDW [19], a distinction was made between vehicle type. Unfortunately, loop detectors with this information were not located on the selected merging taper locations, or upstream or downstream of these locations. Therefore, values were chosen which are realistic for Dutch motorways. Different from the values for taper-length and traffic flow, only one low value and one high value was chosen for this factor. The low value was fixed on zero percent, and the high value is fixed on 20 percent. With these values, it is more likely to obtain significant results compared to choosing several values varying over the uniform distribution. If for example a scenario would have taken into account with very few heavy vehicles, the participant could still have a conflict course with a heavy vehicle. Although the percentage of heavy vehicles was very low, one single heavy vehicle could have influenced the results in such a way that no significant effect was noted as a result of the of heavy vehicles.

Table 4.8: The factor's values used in each scenario. A plus or minus in between brackets indicates whether a value is chosen from a low range or high range.

Section	Taper-length [m]	Traffic flow left roadway [veh/h]	Traffic flow right roadway [veh/h]	% of heavy vehicles left roadway
S1	140(-)	1898(-)	2011(-)	0(-)
S2	190(+)	1851(-)	2063(-)	20(+)
S3	100(-)	2441(+)	1842(-)	20(+)
S4	230(+)	2956(+)	1902(-)	0(-)
S5	120(-)	1954(-)	2869(+)	20(+)
S6	250(+)	2097(-)	2780(+)	0(-)
S7	160(-)	2717(+)	2311(+)	0(-)
S8	210(+)	2567(+)	2462(+)	20 (+)
S9	750	2200(+)	2200(+)	20 (+)

The scenarios defined in table 4.6 were all placed in the experimental road design, which must be completed by all participants. The sequence in which the scenarios are presented to the participants may influence the results. Participant's driving behaviour may change towards the end of the experiment due to for example tiredness and lowering concentration. In order to prevent biased results, different experimental road designs were designed in which the sequence of the scenarios was different (see table 4.9). In each experimental road design, a scenario was placed in a different quarter of the experimental road design. The same holds for the standard geometric design, which is shown in bold in table 4.9.

Due to a lack of computational power of the driving simulator, it was necessary to split each experimental road design in two sub-road designs. The lack of computational power resulted in shaking pictures, which would have a negative effect on the driving simulator's realism. Besides, the traffic simulation in VISSIM may not have been fast enough which would have resulted in traffic driving too slow. As a result of splitting the experimental road designs, less vehicles must be computed at the same time and thus less computational power was needed. Each sub-road design consisted of four or five scenarios, and is completed consecutively. For the participants it was clear at which point the first sub-road design was completed. The experiment was then interrupted, after which the next sub-road design was started.

Table 4.9: Four experimental road design, with each a different sequence of nine scenarios.

Experimental road design	Scenarios
1	S5-**S9**-S6-S1-S2-S7-S8-S4-S3
2	S3-S4-S5-**S9**-S6-S2-S1-S7-S8
3	S8-S7-S3-S4-S6-**S9**-S5-S2-S1
4	S1-S2-S8-S7-S4-S3-S6-**S9**-S5

Sample size A minimum number of participants was needed to collect a sufficient amount of data so that well founded conclusions could be drawn. Data from previously conducted studies or a pilot study was needed to determine the sample size of the experiment. With this data, the variability and standard deviation of the factors can be calculated, and subsequently the sample size. However, no data was available on this topic which could have been be used to determine the sample size. As a result, a target sample size was determined prior to the final experiment. A minimum sample size of 30 valid participants is broadly accepted, but also questioned in literature [78]. Assuming that a part of the datasets is invalid, the aim was to find 40 participants for the driving simulator experiment. A participant was able to finish the experiment in one hour, and thus a minimum of four days were needed in order to complete the driving simulator experiment.

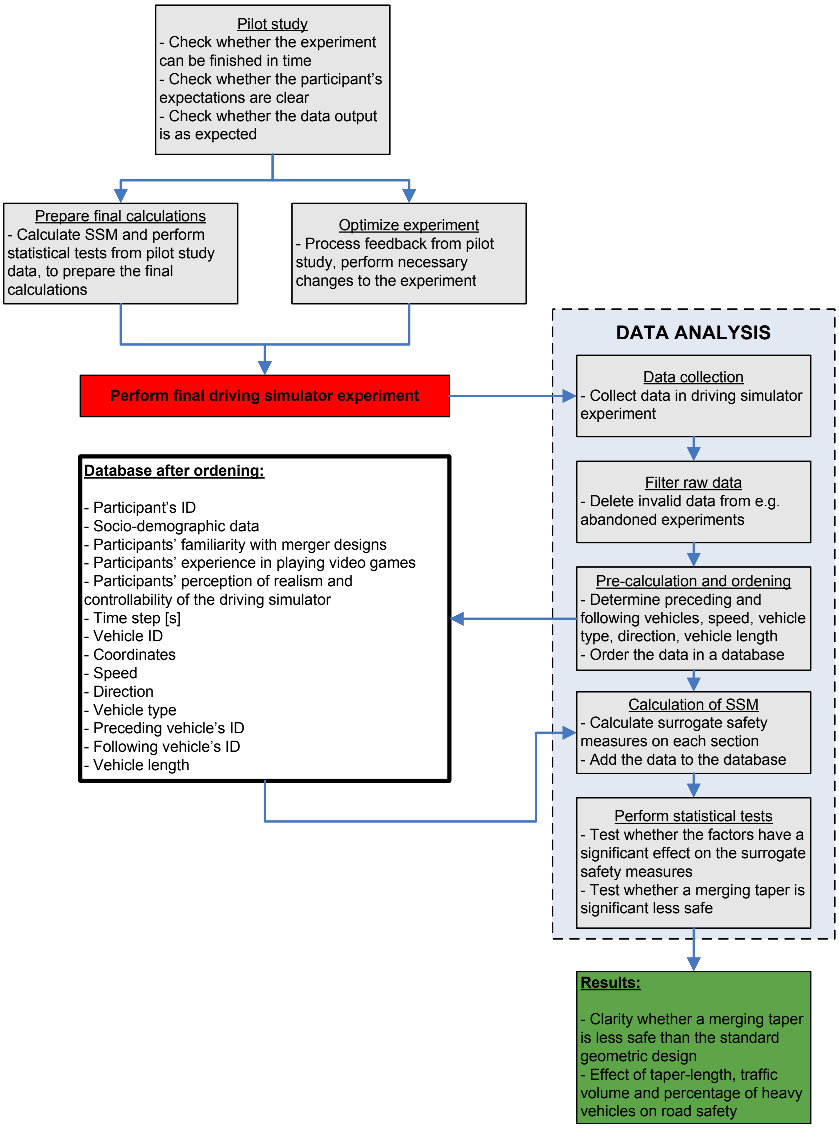


Figure 4.10: Flowchart with the data analysis steps for the driving simulator experiment's data. Segment A is located upstream of the gore, segment B and C are located on the tapered lane and segment D is located downstream of the taper-point.

Accuracy of the method The usage of the method described above had some downsides, which are discussed below. During the driving simulator experiment, VISSIM collected all relevant data (timestep, coordinates, speed, vehicle type) in text files. Using Matlab, participants' vehicle data was extracted and all corresponding data was ordered per vehicle. Thereafter, vehicles were assigned to a lane in each time step so that the distance between subsequent vehicles can be calculated. After this information was determined, the surrogate safety measures were calculated. Assigning vehicles to lanes was done as follows: lanes' axis were defined in Matlab, and vehicles were assigned to the nearest axis which was calculated from vehicles' coordinates in each time step. The centre point of the vehicle was taken into account in all measurements. Using this method caused an error in assigning vehicles to lanes. At the downstream end of the tapered lane, the tapered lane had a relative small width compared to the adjacent through lanes. Thus, the distance from the axis of the lane to the side of the lane was relatively small. As a result, vehicles on adjacent through lanes might have been assigned unfairly to the tapered lane. At the point of the gore, this error does not exist since all lanes have the same width. At the taper-point, this error only occurred if vehicles were located less than 0,88 m from the side of the tapered lane. This distance increased linear from 0 m at the point of the gore until 0,88 m at the taper-point. As a result, at some time steps the surrogate safety measures were not calculated correctly. For example, the vehicle's headway might suddenly have changed if the participants' vehicle was wrongly assigned to another lane. When analysing the lanes on which the participants drove, the share of participants who drove on the tapered lane was slightly higher than it actually was. This error appears on every scenario, so when comparing the driving behaviour on different scenarios this error was ignored. In the collected data, the vehicle type (car, truck) of each vehicle can be found. In the driving simulator, varying 3D-models were assigned to each vehicle type "car". As a result, person cars in the simulation had different lengths which cannot be determined from the collected data. Since the centre point of the vehicle was taken into account in all measurements, the length of the vehicles must be known when calculating surrogate safety measures. The average vehicle length in the simulation was 4,3 m, with a minimum length of 4 meters and a maximum length of 4,6 meter. Assuming a driving speed of 100 km/h, the maximum headway error would be 0,02 s. Since this error is very small, and the error occurred at every scenario, this error was ignored in this study.

In every time step, a predecessor was determined using the method discussed above. At the mergers, data was collected from 110 m upstream of the point of the gore until 250 meters downstream of the taper-point or 250 m downstream of the lane drop. In some cases, the predecessor of the participant drove outside the measurement area, and therefore sometimes no predecessor was determined while one was present in the experiment. As a result, no measurement was taken into account for time headway, while a relative large value should have been measured. In the final results, it could have been possible that for a participant who keeps a large time headway, the mean time headway is relative low because the large distance headway values were not measured. Therefore, if no distance headway measurement was found, a predecessor with accompanying distance headway was assumed at the end of the data collection zone from which the time headway was then calculated. At the end of the data collection zone, small distance headways and thus small time headway values were measured as a result of this assumption. However, the mean time headway value for each participant became more realistic compared to the calculations performed without this assumption. For measurements such as time to collision, this assumption was not applied because assuming the predecessor's speed would make the calculation very inaccurate.

4.3.6. DATA COLLECTION AND DATA PROCESSING

Vehicle's data was collected 10 times per second using the integrated function *direct output* of VISSIM. Text file were created as output files, and contained different data types. In order to calculate the surrogate safety measures, the following data was collected:

- **Timestep [s]**. Gives the timestep in the simulation on which the data is collected.
- **Vehicle ID**. Gives the vehicle ID.
- **Link/lane number**. Indicates on which link and lane each vehicle drives.
- **X/Y-coordinates**. Gives the X- and Y-coordinate of each vehicle. Coordinates are tracked on the middle of the front of each vehicle.
- **Headway [m]**. Gives the headway between the front of two preceding vehicles on the same link.
- **Vehicle length [m]**. Gives the length of each vehicle.
- **Speed [m/s]**. Gives the speed of each vehicle in each timestep.
- **Acceleration**. Gives the acceleration (positive or negative) of each vehicle in each timestep.
- **Vehicle length**. Gives the length of the simulated vehicle.

- **Vehicle type**. Gives whether a vehicles is a person car or heavy vehicle.

Data was collected on the complete merger including the turbulence distance upstream and downstream of the merging taper. The turbulence length is chosen because it is defined as the length over which the road user behaviour is influenced by a discontinuity [21]. The turbulence distances upstream and downstream of a merger over which data is collected are given in table 4.10.

Table 4.10: Distances upstream and downstream of a merger, over which data is collected in the driving simulator experiment.

	Merging taper	**Standard geometric design**
Upstream	110 m from the point of the gore	110 m from the point of the gore
Downstream	275 m from the end of the taper	110 m from the end of the expelling marking

After the data has been collected, the data was analysed in different steps. A flowchart of the data analysis is shown in figure 4.10. The first step in processing the data was to filter the data in order to delete the invalid datasets. Datasets could be invalid because of several reasons, for example due to unexpected events during the experiment which influences the participant's driving behaviour. One of the events which occurred during the experiment was a crash of VISSIM, which resulted in vehicles continuously driving in the last given direction instead of anticipating on other vehicles and road environment. It has shown that vehicles' coordinates generated by VISSIM were sometimes not converted to visible objects in the environment, which resulted in disappearing vehicles and invisible vehicles. When such events occurred, the dataset from the specific participant on the specific scenario was deleted since these events are unrealistic, but influenced the participant's driving behaviour.

Sometimes, participants crashed with a simulated vehicle or with for example a guide rail. It was possible for participants to drive through one or multiple simulated vehicles, and continue their route in the experiment. Three to six accidents per scenario occurred during the experiment. The exact number of crashes can be seen in table 4.11.

Table 4.11: Number of accidents occurred in the experiment, sorted by scenario.

Scenario	1	2	3	4	5	6	7	8	9
Nr. of accidents	3	4	5	4	5	3	6	5	4

The number of accidents during the experiment was much higher compared to real life merging taper locations. The road design and traffic conditions in the experiment were similar to real life merging tapers. Therefore it is expected that the high number of accidents was caused by other factors than the merging taper itself. In the second questionnaire, which is conducted after the experiment, participants stated they had difficulties in controlling the vehicle during the experiment. It is expected that this was caused by the driving simulator vehicles' hardware and translation from participant's steering to steering in the simulation. Besides, there were difficulties in judging other vehicles' speed and location based on the simulated graphics. Taking into account the high number of accidents compared to real life and the outcome of the second questionnaire, it was expected that the accidents in the driving simulator were caused by difficulties with the driving simulator vehicles' controllability. Therefore, it was decided to delete the datasets from the specific participant and specific scenario, in which such an accident occurred.

In order to proceed with the data analysis in Matlab, the coordinates of the relevant merger were imported in Matlab. To do this, the axes of the lanes were drawn in an Inkscape file based on the coordinates which are used in the Autocad drawing, which is the basis of the geometric design in the driving simulator. Matlab read the coordinates of the Inkscape drawing in order to locate the lanes on a merger. The collected data is then imported in Matlab, and it was calculated on which lane each vehicle drove in each time step. Then, the preceding vehicle and following vehicle were determined for both the participant's lane as the participant's adjacent lanes. A database was constructed in which the data for each participant's vehicle was saved. The participant's ID, time step, coordinates, speed, direction, vehicle type, preceding vehicle's ID, following vehicle's ID and vehicle length was stated in the database.

Surrogate safety measures were calculated from the data in the database using Matlab. Based on the coordinates measured in the driving simulator experiment and the coordinates from AutoCAD, it was possible to assign all measurements to locations in the experimental road design. In this way, it was possible to compare the driving behaviour measured on different merger designs. As a last step in the data analysis, statistical tests were performed in order to find statistically significant effects of taper-length, traffic volume and percentage of heavy vehicles on surrogate safety measures.

Before the final experiment was performed, a pilot study was conducted. In the pilot study it was checked whether the experiment can be finished within the time period. It was also checked whether the data output contained the data which was needed for the analysis. After the pilot study, the complete data analysis which is shown in figure 4.10 was performed in order to check if the data output was sufficient. The data analysis was performed using Matlab scripts. In the final driving simulator experiment, the same Matlab scripts were used to perform the data analysis. The feedback from the pilot study was processed after the pilot study, which have led to minor changes in the final experiment.

Questionnaires were performed in Google Docs, which is an online tool in which for example questionnaires can be designed. After deleting the invalid data, results were exported in an Excel file in which also the data analysis was performed. The questionnaires are discussed in more detail in section 4.4.

4.3.7. INNOVATIVE APPROACH

As discussed in this section a driving simulator was used to measure road safety, which is an innovative method. Each driving simulator which is used for road safety purposes has each unique characteristics, and it's own innovative components. The driving simulator which was used in this study has been developed by Witteveen+Bos, and has been adjusted to make it as suitable as possible for road safety study purposes.

The innovation in this study's driving simulator was particularly related to the simulation of other traffic in the experiment, and building up the environment. Other traffic in the experiment was simulated by the microscopic simulation program VISSIM, and the participant's vehicle was integrated in the dynamic simulation process. This means that the remaining traffic reacts on the driving behaviour of the participant. The connection between VISSIM and a driving simulator is unique, and therefore this is a very innovative component in this study. The environment which was used in the driving simulator has been created with programs such as AutoCAD which are conventional in the road designing process, but are quite innovative in driving simulators. The advantage of using these programs as an input for the environment is that the environment can be adjusted very fast and easy. It is for example possible to test the road safety of a certain road design during the designing process.

To summarize, using a driving simulator for road safety purposes is an innovative approach, and even more innovative components were added to the driving simulator used in this study. Of course, innovation comes with certain limitations since the components have often never been tested for this purpose. The driving simulator which was used in this study also showed some limitations, for which further research may be useful. These are described in the last chapter of this report.

4.4. QUESTIONNAIRE

As described in section 2.3.4, the questionnaire has several purposes. Based on that, the questionnaire consists of four parts, of which part 1, part 2 and part 3 are performed prior to the driving simulator experiment, and part 4 is performed after the driving simulator experiment. The four parts are stated below:

- **Part 1:** Socio-demographic data.
- **Part 2:** The driver's familiarity with merging tapers and the standard geometric design, and their perception of safety on both designs.
- **Part 3:** The driver's experience with playing video games.
- **Part 4:** The driver's perception of realism of the driving simulator's environment and the simulated vehicle's behaviour. Also the participant's perception of controllability of the driving simulator's vehicle was asked in this part.

The questionnaire started with a short explanation about the purpose of the questionnaire, and the estimated duration was given. Similar to the data which was collected in the driving simulator, the questionnaires were completed anonymous. However, the time stamp of the questionnaire was saved which makes it possible to link the questionnaire's data with the data collected in the driving simulator.

Part one of the questionnaire collected socio-demographic data such as age, gender, driving experience and occupation, with which was checked if the participants group was representative. Part two asked for road user's familiarity with merging tapers and the standard geometric design. Relative subjective road safety was measured in part two, by asking which merger design was perceived more safe. Part three obtained information about the participant's experience with playing video games, so that a possible link between gaming experience and driving behaviour in the driving simulator could be found. Part four was important to give an assessment on the driving simulator's realism. Questions were asked about the realism of the driving simulator's environment, the simulated vehicle's behaviour and controllability of the driving simulator's vehicle. A clear view on the driving simulator's realism is important, since it influences the participant's driving behaviour. If for example the driving simulator was perceived very unrealistic, this must be taken into account in interpretation of the results.

In order to obtain the right answers from the asked questions, the questions must have met several requirements. For example, each question must be understood well, otherwise participants could have answered the question with a wrong intention. In the designing process of the questionnaire, the following requisites were taken into account [79]:

- The questionnaire must be clear and easy to understand.
- The lay-out is easy to read.
- The sequence of questions must be easy to follow.
- The content of the questions must be specific.
- The questions must be free from assumptions.

Mathur [80] validated the driving simulator and simulated environment used in his experiment by means of a questionnaire. The driving simulator was evaluated based on the participants' experience. The complete questionnaire was not given in the paper, but was designed as follows: Participants rate the simulator components (e.g. steering wheel, pedals) compared to their real-world experience on a scale of 1 to 7, which is called the Likert-scale. Indicating 1 means unrealistic conditions and 7 indicates very realistic conditions.

Witmer [73] developed a questionnaire which is called the Presence Questionnaire (PQ). This study is relative old, but it is still cited many times in recent studies in which the PQ is used as a basis for a new developed questionnaire. The initial questionnaire measured the degree to which individuals experienced presence in a virtual environment. The first version of the PQ was used in four driving simulator experiments. The overviewing paper of Van Baren [81] stated that consistent results were obtained in the studies in which the PQ was used. Banos [82] developed a new questionnaire called the “Reality judgement and presence questionnaire” in which questions were derived from the PQ of Witmer [73] and additional literature. The first version of the "Reality judgement and presence questionnaire" contains 77 questions. Questions in the final version of the questionnaire were derived from the first version, and contains 18 questions. Questions exist in three dimensions, namely *reality judgement*, *internal/external correspondence* and *attention/absorption*.

A more recent study on driving simulator questionnaires is the study of Burnett [71]. He stated that presence is important in the virtual reality domain, since there often exists a close link between an individual's experience of a virtual environment and their subsequent driving behaviour. Burnett designed a questionnaire "specifically to enable researcher and practitioners to understand how participants perceived the driving simulation environment in relation to real-world equivalent situations”, and is called the "Driving Simulator Experience Questionnaire (DSEQ)". The final questionnaire designed in this study is informed by 20 interviews and focus sessions, 5 expert reviews, simulator studies involving 225 people across different fidelity simulators and research institutions. In the final questionnaire, the questions are related to the following [71]:

- Strategic (e.g. "I felt as if I had been on a journey").
- Tactical (e.g. "I was compelled to obey the displayed road signs").
- Control (e.g. "I had a strong sense of physically controlling the vehicle").
- Social aspects (e.g. "I was aware that other people were driving cars around me").

The questionnaire of Burnett [71] is a questionnaire which is specially developed for presence relevant to driving simulators, while other studies presented more generic presence questionnaires on virtual reality. As discussed above, the content of the questionnaire is checked by specialists and piloted on a large scale. The questionnaire shows reliability by giving a Cronbach's alpha of 0.86, which indicates how closely a set of items are related as a group. It is considered to be a measure of reliability, and is commonly used to test the reliability of questionnaires.

The final questionnaires can be found in appendix C and D. Questions stated in part one were socio-demographic related items which were relative straight-forward. Six out of the nine questions were derived from HF Auto project's questionnaire [74]. Items from this questionnaire were recommended to be used in all experimental researches that involves automated driving. Questions in part two and part three of the questionnaire were unique questions which were not derived from an existing questionnaire. These questions were designed keeping the requisites from Venkitachalam [79]. In part four of the questionnaire in this thesis, Burnett's questionnaire was used. This questionnaire was regarded as a valid and reliable questionnaire, which was used in several driving simulator studies. In the pilot study, it was checked whether these questions are valid, i.e. if the questions were easy to understand, and if the right answers were given to the questions.

4.5. DATA ANALYSIS

4.5.1. SURROGATE SAFETY MEASURES

Surrogate safety measures were selected for the data analysis. Both time headway and time to collision were chosen because they have been used in many studies, and are widely discussed in literature. Studies of Evans [59] and Michael [60] concluded that small time headway values are directly linked to accident-frequency. Studies of the U.S. Department of Transportation [49] and St-Aubin [46] mention that small time to collision values indicate a high accident-probability and thus a low road safety. Furthermore it was mentioned that time to collision has a stronger link with road safety, as the speed difference is taken into account in this surrogate safety measure. Time to collision values which are higher than 50 seconds were deleted prior to the analysis because their predictive power is very low according to St-Aubin [46].

Besides the participant's driving speed and number of lane changes were taken into account as output variable. Studies of Aarts and Van Schagen [30] and Elvik [24] described the relation between absolute driving speed and the accident-probability. It was stated that the accident-probability is high if the absolute speed is high. Lane changing indicates a disturbed traffic flow in which road users move in a lateral direction which is relative unsafe driving behaviour. The study of Jula [83] stated that lane changing is one of the riskiest manoeuvres that a driver has to perform on a conventional motorway.

In this study, speed variability was not taken into account as a road safety indicator. It was expected that speed variability on merging tapers was high compared to the standard geometric design, as a relative short merging length may cause decelerating and accelerating in order to find an acceptable gap to merge. For this reason, it was expected that speed variability is high on merging tapers with a short taper-length. It was expected that speed variability is high on merging tapers with a high traffic volume. If relative many vehicles are present on a merging taper, it is expected that road users must accelerate and decelerate to find an acceptable gap. As heavy vehicles have a relative low driving speed, it is expected that speed variability is high if heavy vehicles are present. However, due to low controllability of the driving simulator it is expected that the results on speed variability will not be realistic. For example deceleration behaviour is non-realistic due to the driving simulator characteristics. Therefore, speed variability is not taken into account as a road safety indicator.

4.5.2. MERGING TAPER VERSUS STANDARD GEOMETRIC DESIGN

In order to test whether the safety of driving behaviour on merging tapers is unsafe compared to the standard geometric design, the average driving behaviour on all eight merging taper scenarios was compared with the standard geometric design. For example, the headway measurements of each single participant measured on a merging taper scenario was averaged to one value which represented the headway measurement on all merging taper scenarios. This results in two correlated groups, since each participant completed both the merging taper scenarios and the standard geometric design scenario.

The paired samples t-test was used to determine whether the mean difference between correlated observations was statistically significant different. This statistical test was valid to be used because two correlated groups were present (the same participants complete all merging taper scenarios and standard geometric design scenario) and one dependent variable was present (for example time headway). As discussed in chapter 3, it was expected that the driving behaviour on merging tapers was less safe compared to the standard geometric design. The safety of driving behaviour was determined by calculating multiple surrogate safety measures. Therefore, the null hypothesis for the paired samples t-test was that the mean difference between the surrogate safety measures' values is equal to zero. The hypothesis was that the safety of driving behaviour on merging tapers is lower compared to the standard geometric design, so it was expected that the null hypothesis will be rejected.

4.5.3. FACTORS' EFFECT ON SURROGATE SAFETY MEASURES

In order to find the effect of taper-length, traffic volume and the percentage of heavy vehicles on the output variables, the data was plotted in boxplots and were sorted from factors with a low level to factors with a high level. The graphs were analysed to find possible trends in the data. For example small time to collision values were expected on merging tapers with a short taper-length compared to merging tapers with a long taper-length. This type of analysis was done for each of the factors (taper-length, traffic volume on the left roadway, traffic volume on the right roadway, percentage of heavy vehicles) for the different output variables (time headway, time to collision, driving speed, number of lane changes). Of course, due to the experimental design, the output variables on each scenario may also have been affected by the level of the other factors. For example when analysing taper-length, the level of the traffic volume differed for each level of taper-length. This possible effect was taken into account in the data analysis.

In addition to the visual analysis described above, a linear mixed model (LLM) was estimated in SPSS to analyse the effect of the factors on the output variables. The LLM is used to estimate both main effects of the factors and interaction effects between the factors. A LLM is a statistical model to predict continuous outcome variables by both fixed factors and random factors. The LLM is an appropriate model because the driving simulator study is a repeated measures study, in which the participant's driving behaviour was measured repeatedly on up-following segments. According to West et. al [84], the name LLM comes from the fact that the models are linear in the parameters, and that the independent variables may involve a mix of fixed and random effects. "Linear in the parameters" means that no parameter appears as an exponent or is multiplied or divided by another parameter. Fixed effects may be associated with continuous independent variables [84] such as weight or test scores, or with factors which are categorical such as gender or treatment group. According to West et. al [84], "fixed effects are unknown constant parameters associated with either continuous independent variables or the levels of categorical factors in an LLM. Estimation of these parameters in LLMs is generally of intrinsic interest, because they indicate the relationship of the independent variables with the continuous variable". Random effects are represented by (unobserved) random variables, which can take a set of possible different values in contrast to fixed variables. A random variable in an experiment may be a person's height when choosing a person at random. In this study, the LLM was used to analyse the effect of the factors (taper-length, traffic volume, percentage of heavy vehicles) on the output variables (for example time headway and time to collision). The build-up of the model is discussed in more detail in subsection 5.3.4.

A LLM described above is first estimated with values which are determined over the complete data collection area. In the second part of the analysis, the area was split in four segments which can be seen in figure 4.11, and in each segment the output variables were calculated to find how driving behaviour varied over the four segments. Segment A covered upstream of the point of the gore, segment B covered the first half of the tapered lane, segment C covered the second half of the tapered lane and segment D covered downstream of the taper-point.

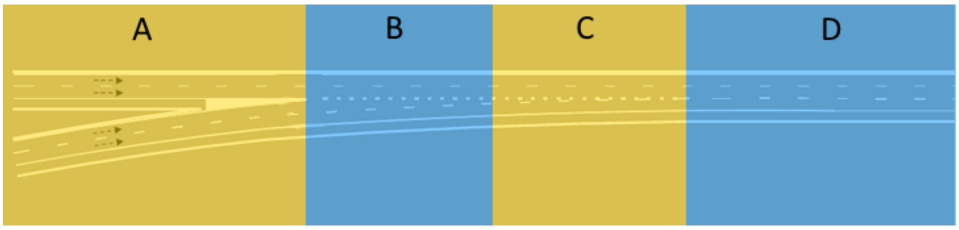


Figure 4.11: Four segments on merging tapers which are used for the data analysis.

5

RESULTS

5.1. ACCIDENT DATA ANALYSIS

Accident data from 2010 to 2013 is analysed in order to get a first insight in the number and type of accidents on merging tapers, and the effect of taper-length and traffic volume on the number and type of accidents. Accidents are registered in BRON [22] (Bestand geRegistreerde Ongevallen Nederland) which is owned and managed by Rijkswaterstaat. The first subsection shortly repeats which existing merging taper locations were taken into account in the analysis of registered accident data. In subsection 5.1.2, the data quality is discussed. The last subsection presents the conclusions based on the data analysis.

5.1.1. DATA ANALYSIS

Accident data is collected following the method which is discussed in chapter 4. Eight locations were selected which comply with the description of a representative merging taper (see table 4.1). In BRON [22], accidents are registered with a certain severity level, which may be *fatal*, *first aid injury*, *only material damage* or *other injuries*. BRON [22] does not give a definition of these severity levels. The severity levels *fatal*, *first aid injury*, *only material damage* are levels of which the definition is self-explaining. However, the level *other injuries* is a vague level without a given definition. On the eight merging taper locations from table 4.1, in total 71 accidents were registered in the years 2010 to 2013. Of those accidents, two were *fatal*, two *first aid injury*, two *other injuries* and the remaining 65 were *only material damage*. On the four locations with the standard geometric design, a total of 55 accidents were registered in the years 2010 to 2013. Only at one accident a *first aid injury* resulted, the rest were *only material damage*.

Merging taper versus standard geometric design The number of registered accidents in the years 2010 to 2013 on each representative location is shown in table 5.1. On the merging taper locations, on average 2,2 accidents took place per location per year. On the standard geometric design locations, on average 3,8 accidents took place per location per year, which is 73% higher compared to merging tapers. As the number of accidents on merging tapers is low compared to the standard geometric design, so the results seem to indicate that merging tapers are safe compared to the standard geometric design which was not expected in the hypothesis. However, the difference between the two merger types was mainly caused by standard geometric design location 3. More than twice as much accidents occurred on that location compared to the other to location 1 and location 2. Furthermore the number of representative standard geometric design locations was limited, which may have caused an error in the results.

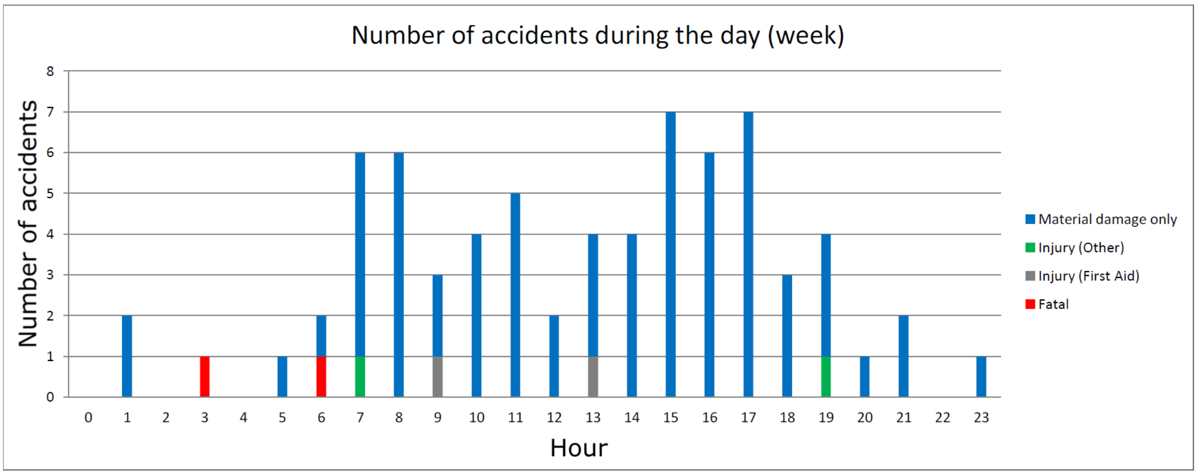
Table 5.1: Number of registered accidents (2010 - 2013) on the merging taper and standard geometric design locations from table 4.1 and table 4.2.

	Name	Location	Number of accidents
Merging tapers			
1	Eemnes	A1-Li 28,2	7
2	Coenplein	A10-Re 32,0	8
3	Waterberg	A12-Li 127,3	15
4	Grijsoord	A12-Re 121,5	10
5	Prins Clausplein	A12-Re 7,7	10
6	Galder	A16-Li 67,0	12
7	Eemnes 2	A27-Li 97,3	1
8	De Baars	A58-Re 36,6	8
Standard geometric design			
1	Leidschendam	A2-Li 43,3	11
2	Holendrecht	A9-Re 23,2	11
3	Ypenburg	A4-Re 47,7	23

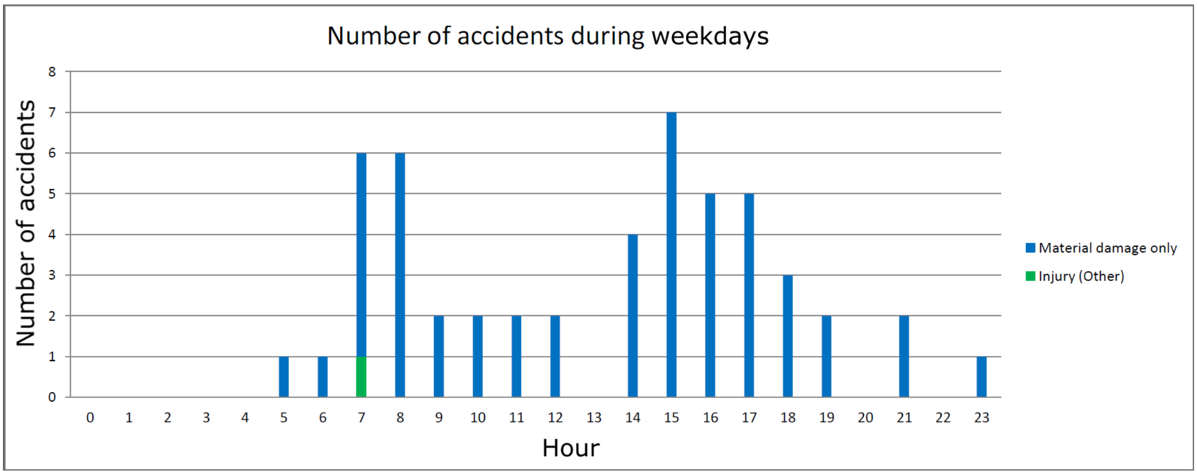
Accidents over time All registered accidents occurred on the representative merging tapers between 2010 and 2013 were plotted over time, and can be seen in figure 5.1. In figure 5.1a, only accidents which occurred during weekday are plotted. It can be seen that the main part of the accidents took place around the peak hours, and especially the evening peak. This might be the result of relative high traffic flows during peak hours.

The difference in the number of accidents during peak hours becomes even more clear in figure 5.1b, in which only accidents on weekdays were taken into account. In this figure, it can be seen that most accidents occurred between 7 and 9 AM, and between 3 and 7 PM. This can also be explained by the traffic volume which was higher in peak hours. The traffic flow graphs can be seen in appendix A. The accident rate over time on weekdays can be seen in figure 5.2. It is defined as the number of accidents per 100.000 passed vehicles and was calculated for each hour. The accident rate was calculated with the average traffic volumes on the concerned merging taper locations, and the total number of accidents on these locations. In figure 5.2, it can be seen that the peaks of the accident rate mostly correspond with the peaks of the average traffic volume. This indicates that the traffic volume has an effect on the accident rate. Three unexpected peaks in the accident rate were found, namely at 5, 21 and 23 hours. From the collected data it can not be said what the cause of these accidents were.

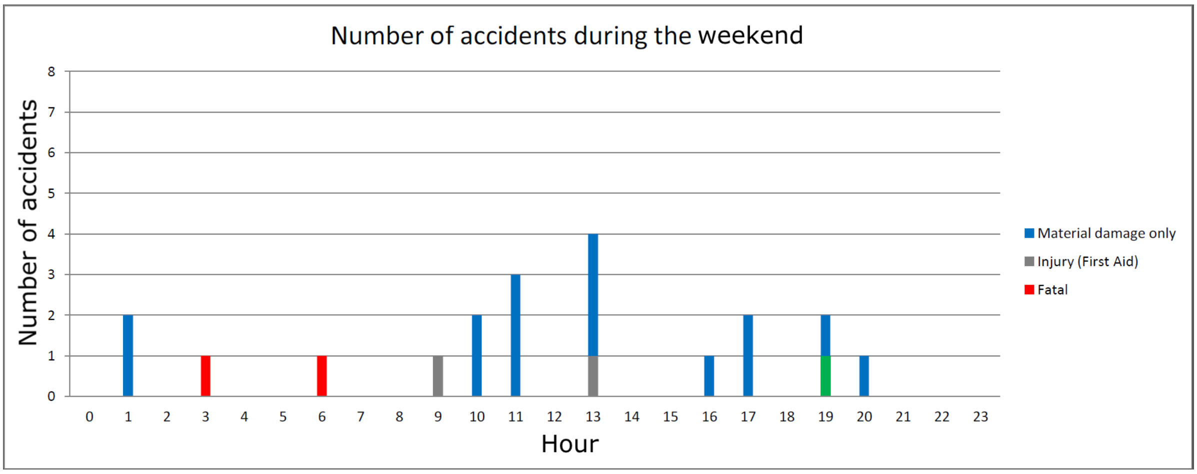
In weekends, accidents mainly occurred at midday which can be seen in figure 5.1c. This might be explained by the fact that in the weekends road users are mostly travelling for leisure, which takes place during the day instead of during peak hours. Besides, in figure 5.1c it can be seen that night-accidents take place during the weekends. When looking at the fatalities and injuries in figure 5.1c, it can be seen that all fatal accidents, and 3 out of 4 injuries take place in the weekends. In 25% of the accidents during the weekend, injuries or fatalities were involved, against 8,5% during weekdays. Fatal accidents in the weekend took place during the night. It might be that darkness or alcohol usage were involved in those accidents. Besides, road users in weekends might be relatively young or inexperienced which might result in more severe accidents. However, these are just presumptions, since this can not be said based on the data.



(a) Accidents during the day, 7 days a week



(b) Accidents during the day, weekdays



(c) Accidents during the day, weekend

Figure 5.1: Registered accidents (2010-2013) on eight relevant merging taper locations (see table 4.1), plotted over time.

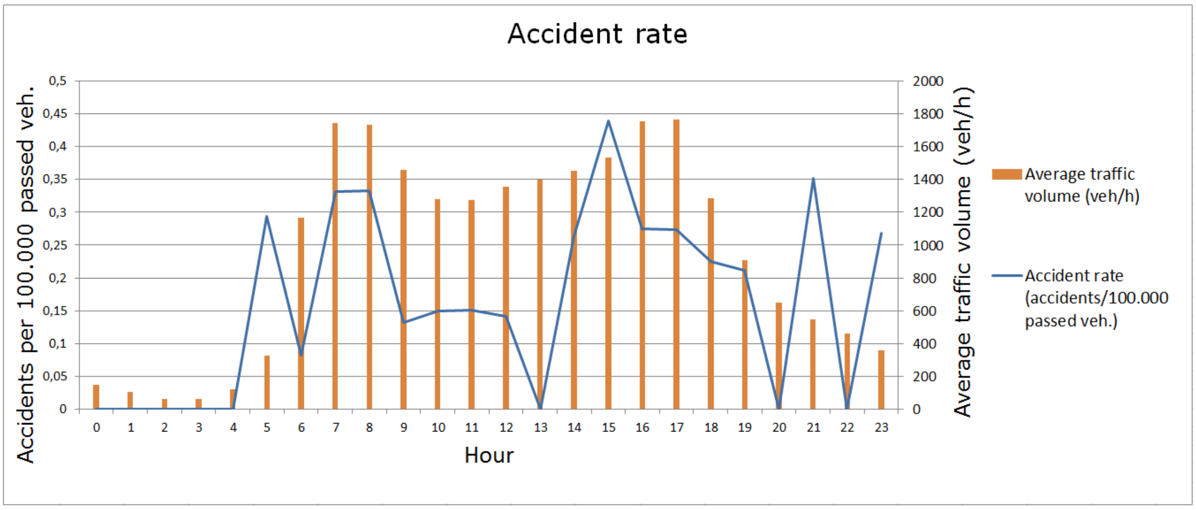


Figure 5.2: Accident rate (accidents per 100.000 passed vehicles) determined based on accident data from 2010-2013 and average traffic volume on the relevant locations (see table 4.1).

Severity and nature of accidents For each level of severity, the type of accident is plotted in figure 5.3. For *fatal* accidents, it can be seen that for one accident the road user drove into a fixed object. A pedestrian was involved in the other *fatal* accident. For the accidents with *injuries*, the type of accident was a side collision or head/tail collision. For the *material damage only* accidents it is notable that the type of accident is unknown for 87 out of 88 accidents. This is probably the result of deficient registering of accident data. When *injuries* or *fatalities* were involved, it seemed to be much more important to collect more detailed information about the accident.

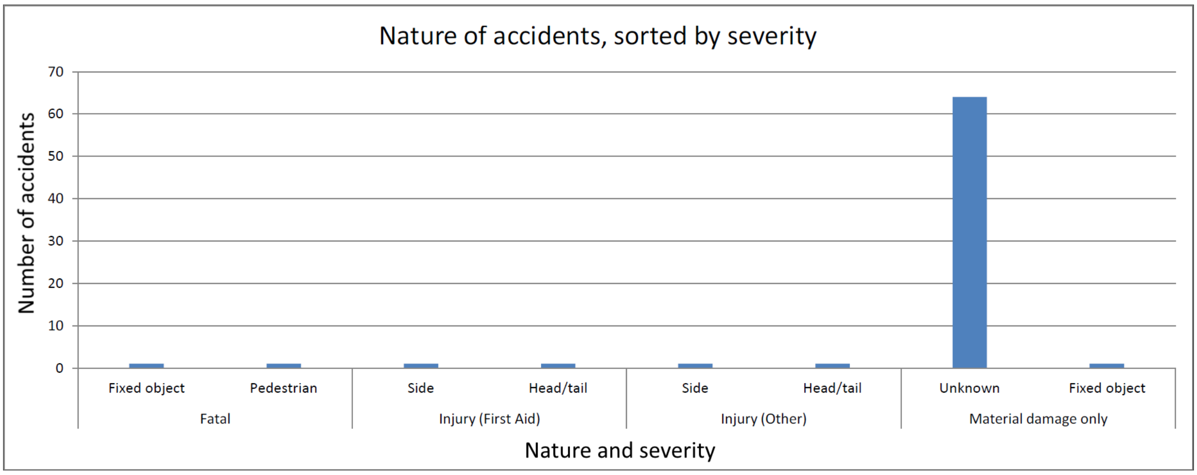


Figure 5.3: Nature and severity of registered accidents (2010-2013) on relevant merging taper locations (see table 4.1).

The effect of taper-length on the number of accidents In figure 5.4 the number of accidents is given for each location, which are sorted by taper-length. The taper-length can be seen in the lower horizontal axis, and the location number on the upper horizontal axis. It can be seen that the most accidents occurred on merging tapers with a middle-long taper-length. The least accidents are registered on merging tapers with a short taper-length, or a long taper-length except for location number 4 on which 10 accidents are registered. This might be a result of high traffic volumes during peak hours, which can be seen in figure A.4 in appendix A. Location number 7 is an interesting location since only one accident occurred on that location, which is by far the least of all locations. The low number of accidents on this location is probably caused by the low traffic volume on that location, which is shown in in figure A.6 in appendix A.

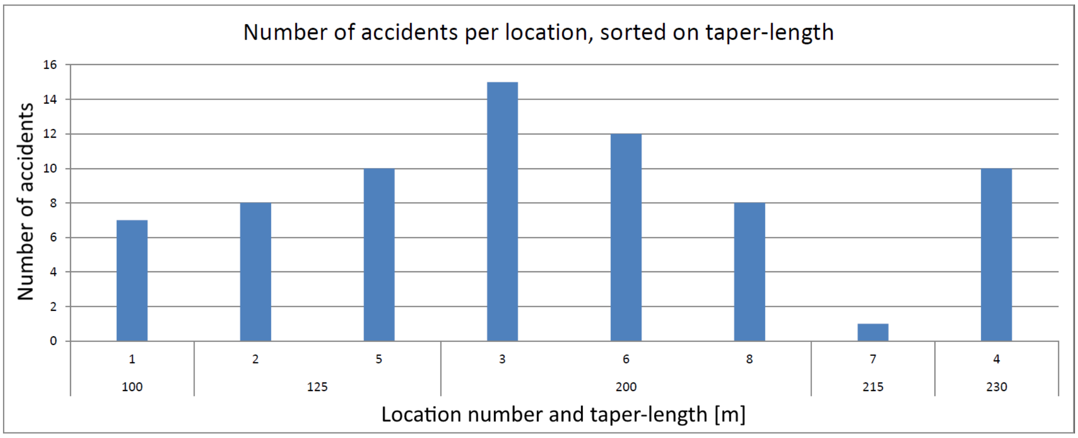


Figure 5.4: Registered accidents (2010-2013) on relevant merging taper locations (see table 4.1), sorted by taper-length and location.

The effect of taper-length on accident-severity In order to see the effect of taper-length on accident-severity, accidents were sorted by severity for every taper-length. This can be seen in figure 5.5. Per taper-length, it can be seen which percentage of accidents ended with *material damage*, *injuries* or a *fatality*. No direct link was found between the taper-length and the severity of accidents. The two accidents which were fatal, both occurred on long merging tapers (200 m and 230 m). Two injuries resulted from accidents on short merging tapers (125 m), but the other injuries occurred on long merging tapers (200 m). Based on these findings, no direct link between the taper-length and severity of accidents is found.

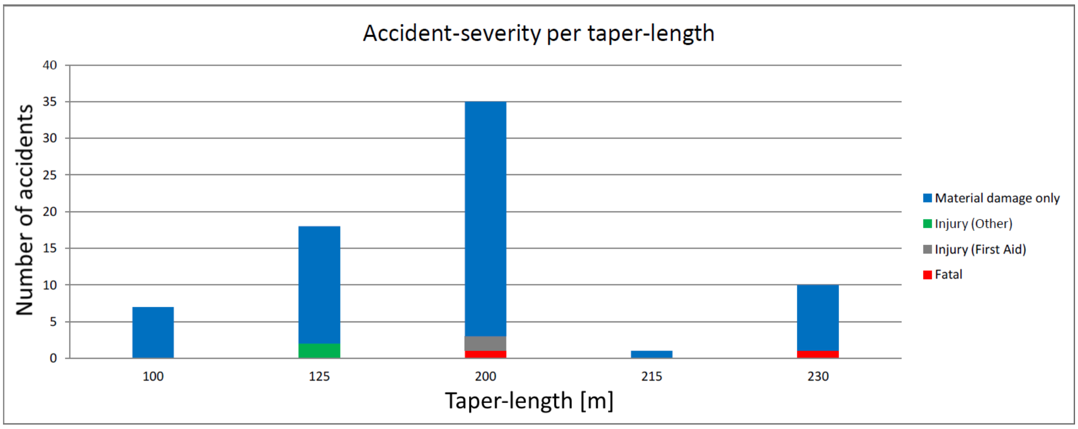


Figure 5.5: Accident-severity of registered accidents on relevant locations (see table 4.1), sorted by taper-length.

5.1.2. QUALITY OF THE DATA

During the data analysis it is important to keep the quality of the data in mind before drawing conclusions. Regarding the accident data, it is not clear what percentage of the occurred accidents is actually registered. It is possible that a non-severe accident occurred, but no police assistance was needed. Then, the accident was not registered. Besides, Vis et al. [85] stated that the overall quality of accident registration is low. Vis also stated that accident registration depends on the severity; severe accidents were registered more often compared to non-severe accidents. Possible causes which were mentioned are the abolition of the standard registration forms which contained detailed information, and intern software problems at the police. Therefore, the amount accidents might be higher than registered in the BRON [22], and the details such as type and severity might be incorrect. A possible effect of the low data quality may be seen in table 5.2, in which the number of registered accidents on merging tapers and the complete national Dutch motorway is presented. It can be seen that the number of registered accidents in 2010 was much lower compared to other years, which might be the result of the abolition of the registration forms [85].

Table 5.2: Total number of registered accidents in BRON [22] on Dutch motorways.

Year	**Registered accidents on relevant merging taper locations ((see table 4.1))**	**Registered accidents on complete national motorway**
2010	1	287
2011	17	1935
2012	31	4834
2013	22	3809
Total	**71**	**10865**

The accuracy of the registered accident location is also debatable. Only one hectometre sign was registered in the data. As a result, the accident might have occurred 100 metres upstream or 100 metres downstream of the registered hectometre sign, which resulted in an accuracy of 200 metres. It is possible that accidents which are taken into account inside the boundaries actually occurred maximum 100 metres outside of the scope. On the other hand, it is also possible that an accident was not taken into account, while the accident occurred in the scope.

Furthermore, from the overall accident data it can be seen that the quality of the data collection is lacking. For example the type of accident was only registered if injuries or fatalities were involved. It seems that for only material damage accidents it was perceived not important enough to include more detailed information. Also experts in the field believed that the quality of the accident registration was lacking in recent years. Apparently, accident data registration was of a higher quality in the past. The quality is clearly lacking in the past years, which was taken into account in the data analysis.

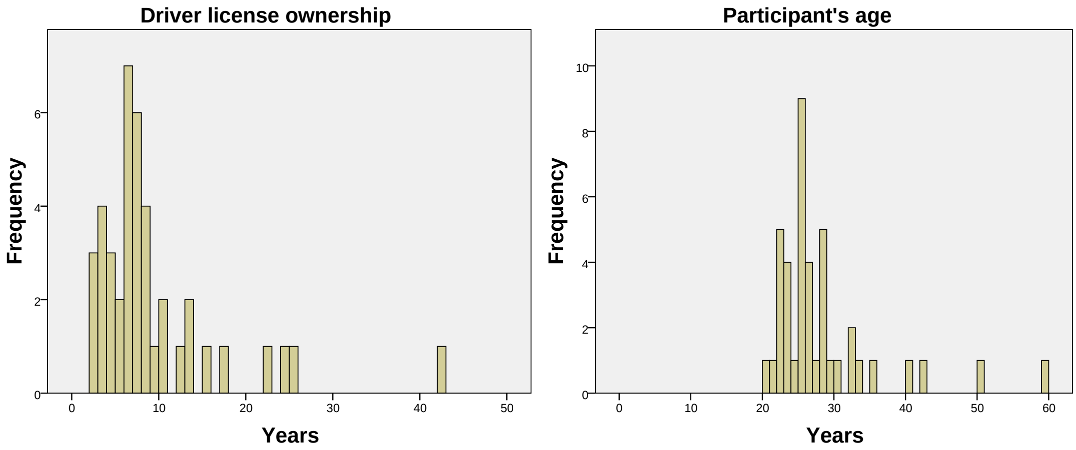
5.2. QUESTIONNAIRE

This section discusses the results of the questionnaire which is presented to the participants prior to the driving simulator study. The questionnaire can be found in appendix C. In total 41 participants joined the experiment, of which 20 participated from TU Delft and 21 from Witteveen+Bos. Characteristics of the participants are given below, and are also shown in figure 5.6.

- 78% of the participants were men, and 22% were women. The high share of men was caused by the gender distribution at the TU Delft and Witteveen+Bos office.
- The youngest respondent was 20 years old, the oldest one 59 years old. The average age of the participants was 27,9 years old with a standard deviation of 7,8 years.
- The duration of the driving license ownership varied between 2 years and 42 years. The average driving license ownership was 8,9 years with a standard deviation of 4,9 years.
- 53,7% of the participants were students, and 41,5% were employed. The remaining 4,8% was part-time employed or unemployed.
- 7,3% of the participants were involved in an accident as a driver, of which 4,9% were involved once, and 2,4% were involved in an accident three times.

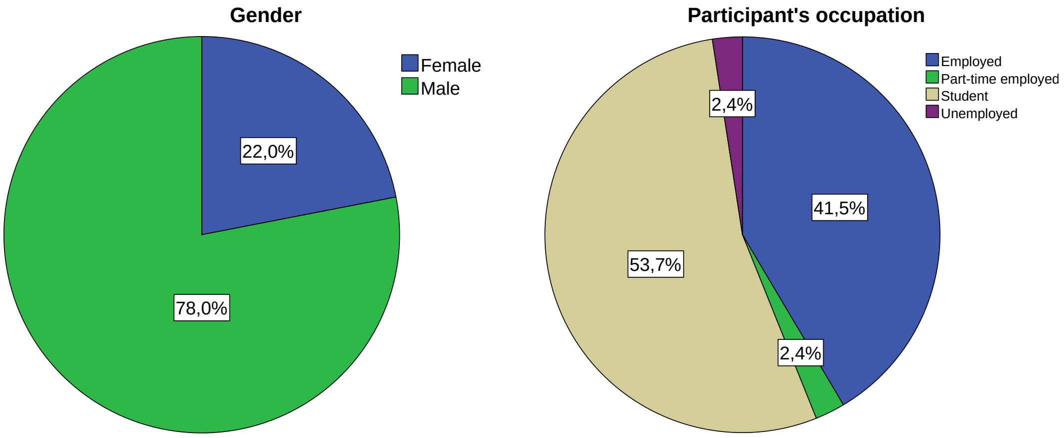
Participants stated in the questionnaire whether they are familiar with the geometric design of merging tapers and the standard geometric design. 97,6% of the participants stated they are familiar with the standard geometric design, and 100% stated that they are familiar with the geometric design of merging tapers. Of the participants who are familiar with both road designs, 65,9% stated they will feel safer on the standard geometric design. 19,5% of the participants stated they will feel safer on merging tapers, and 14,6% stated they will feel equally safe on both geometric designs.

Based on the results stated above, it can be stated that the test group contained a high percentage of men compared to a representative road user group. Besides, the test group's average age was young compared to a representative road user group. As a result, the driver license ownership was also relatively short. It can be stated that all participants were familiar with merging tapers, and nearly all participants were familiar with the standard geometric design. Besides, it can be stated that the greater part (65,9%) of the participants feel safer on the standard geometric design compared to merging tapers. Knowing this, it can be said that the subjective safety of merging tapers is low compared to the standard geometric design.



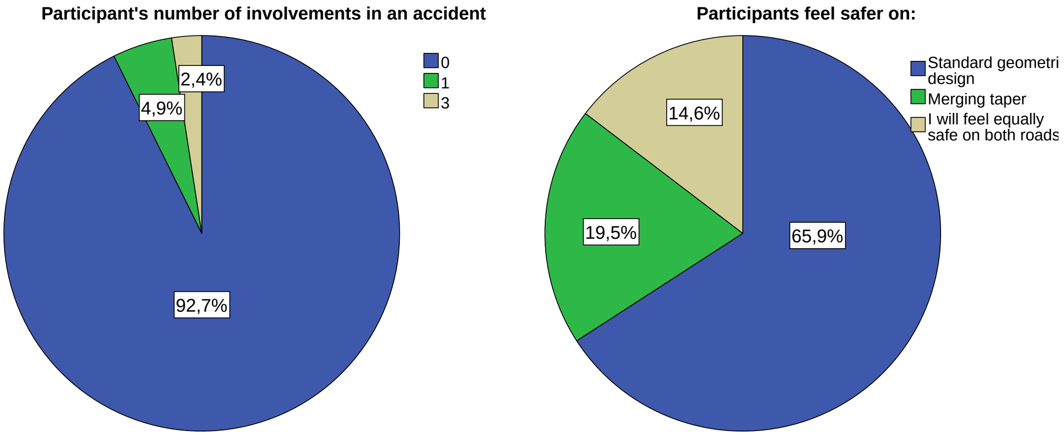
(a) Driver license ownership

(b) Age



(c) Gender

(d) Occupation



(e) Number of accidents per participant

(f) Perceived safety of both merger types

Figure 5.6: Results of the questionnaire performed prior to the driving simulator experiment: driver license ownership, age, gender, participant's occupation, accident involvement, perception of safety.

5.3. DRIVING SIMULATOR EXPERIMENT

This section discusses the results from the driving simulator experiment. First, descriptive data which was collected in the driving simulator experiment is reviewed. Speed, braking manoeuvres, lane choice and lane changing are discussed to get a first insight in the road safety on both merger designs, and the effect of taper-length, traffic volume and percentage of heavy vehicles on the safety at merging tapers. Then, the road safety of merging tapers compared to the standard geometric design is discussed, as well as the effect of taper-length, traffic volume and percentage of heavy vehicles on the road safety on merging tapers. In conclusion, the questionnaire which is performed after the driving simulator study is discussed.

5.3.1. DESCRIPTIVE DATA

Speed Figure 5.7 shows the average driving speed, individual driving speed and standard deviation measured on all eight merging taper scenarios. It can be seen that the average speed slightly decreased upstream of the point of the gore. The decrease of the average speed was larger between the point of the gore and the taper-point. Downstream of the taper-point it can be seen that the average speed increases again. The average speed 110 meter upstream of the point of the gore was 88,3 km/h, and decreased to 83,2 km/h at the point of the gore. On the merging taper, the average speed decreased further to 73,9 km/h at the taper-point. The average speed increased to 77,6 km/h 125 meters downstream of the taper-point. Taking into account the speed limit of 100 km/h, the average driving speed at merging tapers is relatively low. The upper red line in figure 5.7 represents the standard deviation of the driving speed summed with the average speed, and the bottom red line represents the standard deviation of the driving speed subtracted of the average speed. It shows that the standard deviation started to increase around the point of the gore towards the taper-point. The speed variation may be caused by speed variation between participants on the same merging taper scenario, or speed variation between the different merging taper scenarios. The standard deviation decreased downstream of the taper-point. From the individual driving speed plots it can be seen that decelerating mostly took place on the merging taper itself. It shows that many participants came to a standstill, which is the result of a very sensitive braking pedal in the driving simulator. The measured deceleration rates are unrealistic, and therefore only the start location of the braking manoeuvre was taken into account in the up-following paragraph.

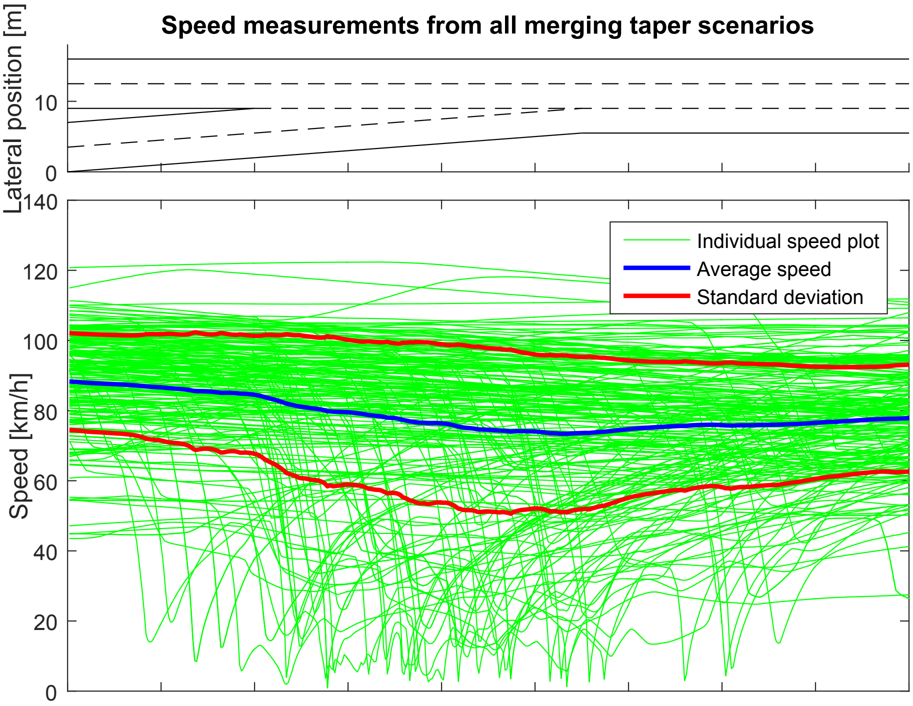
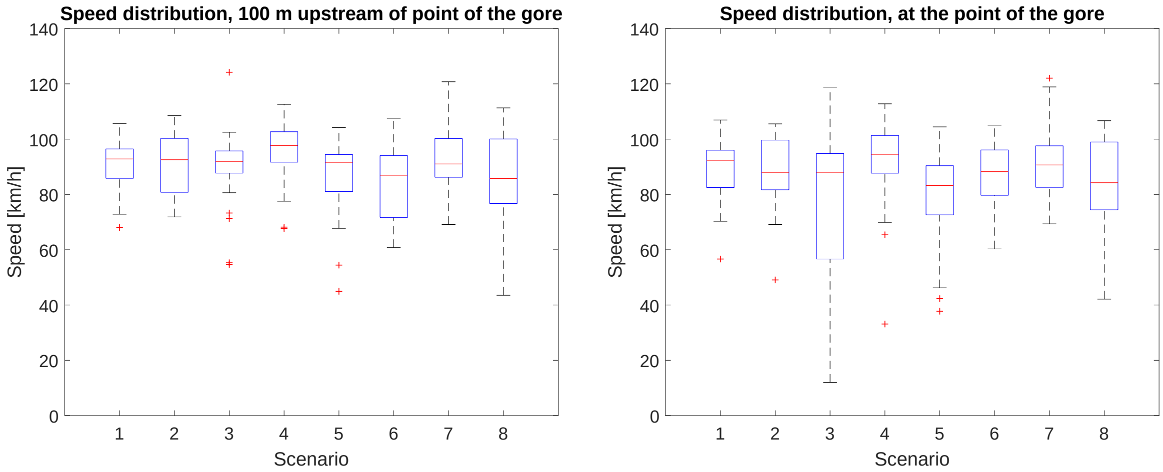


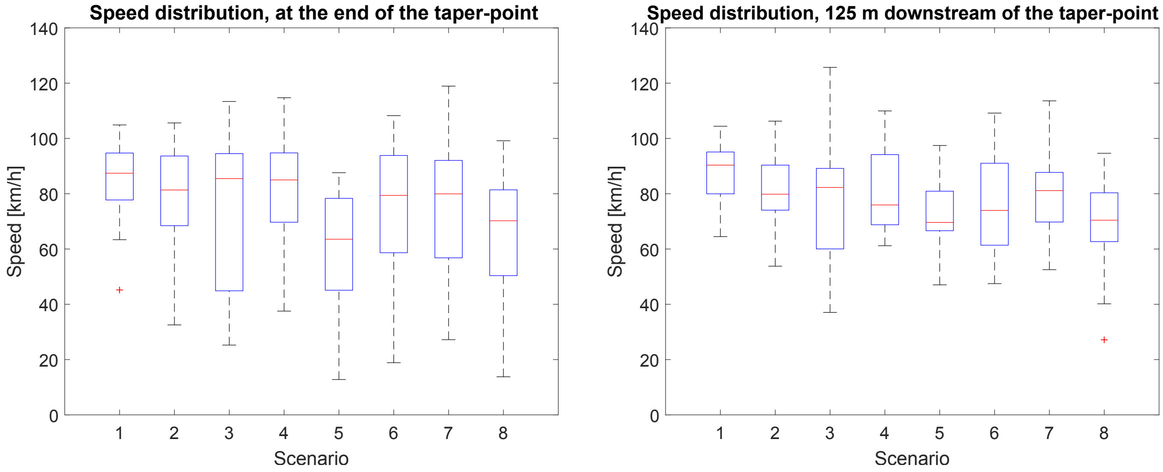
Figure 5.7: Average driving speed, individual driving speed and the driving speed's standard deviation measured on all merging taper scenarios in the driving simulator experiment.

In order to study the speed and speed variation in more depth, boxplots of each separate merging taper scenario are plotted in figure 5.8. This was done at four different locations on each scenario, knowing 100 m upstream of the point of the gore, at the point of the gore, at the taper-point and 125 downstream of the taper-point. 100 meter upstream of the point of the gore, the speed within the separate scenarios was relatively little distributed. The speed at scenario 3 was much less distributed compared to the other scenarios, although most outliers were obtained at that scenario. At the point of the gore and at the taper-point, the speed at scenario 3 was the most distributed compared to other scenarios, although no outliers were measured on these locations. It is suspected that this is caused by a short taper-length (100 m), a high traffic volume on the left roadway (2956 veh/h) and the presence of heavy vehicles (20%). In the hypothesis, it was expected that these conditions cause unsafe driving behaviour such as braking manoeuvres and thus variation in speed measurements. At the taper-point it can be seen that the speed on each scenario is relatively more distributed compared to other locations. Downstream of the taper-point, the speed distribution on each scenario has decreased again. The pattern of an increasing speed variation towards the taper-point which can be seen in figure 5.8 can also be seen in the speed distribution plotted in figure 5.7. It can be seen that the standard deviation from figure 5.7 was caused both by speed variation within merging taper scenarios and speed variation between merging taper scenarios.



(a) 100 m upstream of point of the gore

(b) Point of the gore



(c) End of the tapered lane

(d) 125 m downstream of the end of the taper

Figure 5.8: Speed distribution measured in the driving simulator, plotted separately for each merging taper scenario on four different locations (upstream, point of the gore, taper-point and downstream).

Braking manoeuvres In this analysis, braking manoeuvres were registered each time a participant started braking with a deceleration rate of 3,35 m/s^2 or higher. This value is mentioned by Archer [18] and indicates that a vehicle has a serious conflict. Figure 5.9 presents the start location in longitudinal direction of braking manoeuvres, sorted by scenario. It can be seen that braking manoeuvres on merging tapers (scenario 1 to 8) mainly started around the point of the gore. Braking manoeuvres on the standard geometric design (scenario 9) mainly started towards the lane drop, 750 meters downstream of the point of the gore. Table 5.3 presents the number of braking manoeuvres on each scenario. In the experiment, the number of valid data sets (participants) was not equal for each scenario. To overcome this, the number of braking manoeuvres is divided by the number of participants. It can be seen that the number of braking manoeuvres on scenario 1, 2 and 6 was much lower compared to scenario 3, 5 and 8. The high ratio on scenario 5 might be the result of short taper-length and high traffic volume on the right roadway. The traffic volume on scenario 8 is high on both roadways. At scenarios 1 and 2 the traffic volume on the right roadway is low, therefore it can be argued that the number of braking manoeuvres may be affected by the traffic volume. However, this statement is contradicted by the fact that the traffic volume on scenario 6 is high. The amount of braking manoeuvres per participant on the standard geometric design was much higher than the average amount of braking manoeuvres per participant on merging tapers (2,09 against 0,87).

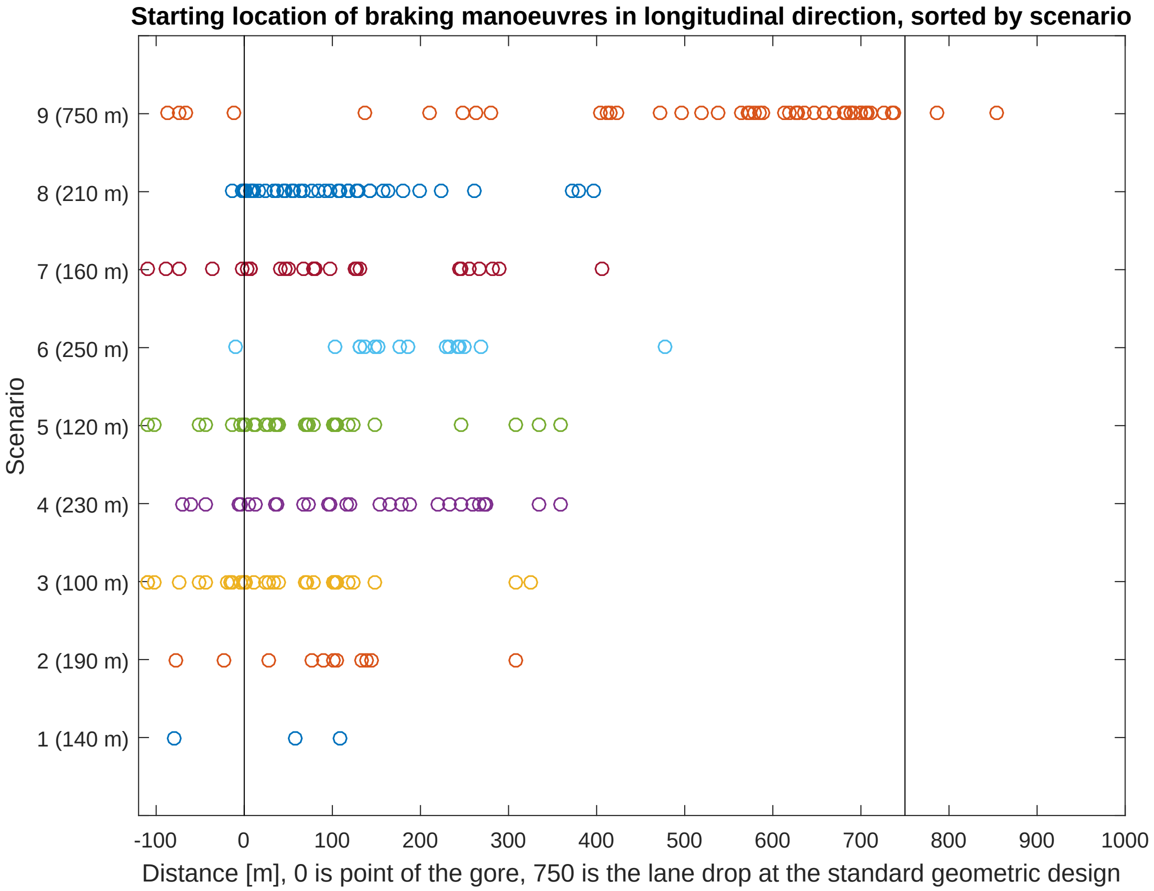


Figure 5.9: Starting locations (in longitudinal direction) of braking manoeuvres measured in the driving simulator, sorted per scenario.

Table 5.3: Average number of braking manoeuvres per participant on a scenario, measured in the driving simulator.

Scenario	1	2	3	4	5	6	7	8	9
Nr. of braking manoeuvres per participant	0,10	0,44	1,19	1,04	1,29	0,62	1,00	1,30	2,09

Lane selection and lane changes In figure 5.10, it can be seen what percentage of participants drove in which lane. The measurements performed on all merging taper scenarios (scenario 1 to 8) were combined in this figure. Each colour represents a lane. Lane 1 represents the left lane on the left roadway, lane 2 represents the right lane on the left roadway. Lane 4 is the tapered lane, and lane 3 is the right lane on the right roadway. The calculation error discussed earlier in chapter 4 can be seen in figure 5.10 at the taper-point, where the percentage of participants driving on lane 4 dropped from around 8% to 0% percent. In the experiment, the number of participants driving on the tapered lane towards the taper-point was less than displayed in this figure. The surplus of vehicles registered on the tapered lane should have been assigned to lane 2 or lane 4. It can be assumed that at the point of the gore the share of participants on lane 2 and lane 3 is correct. The surplus of participants on lane 4 increased linearly between the point of the gore and the taper-point. The maximum error was found at the taper-point, after which the error disappeared downstream (the drop which can be seen in the yellow surface).

From figure 5.10 and table 5.4, it can be seen that 100 meter upstream of the point of the gore, 58% of the participants used the rightmost lane. This percentage decreased slightly to 53% at the point of the gore. Directly downstream of the point of the gore, participants merged to lane 2. Around 180 meters downstream of the point of the gore, the first participant has merged to the leftmost lane. Halfway of the tapered lane, nearly no participants drove on the most left lane. 25% of the participants drove on lane 2, as 54% drove on lane 3. These percentages must be slightly higher due to the calculation error. 17% drove on the tapered lane, but this percentage must be slightly higher due to the calculation error. At the taper-point, 15% of the participants have merged to the leftmost lane, as 56% keeps the rightmost lane. This distribution staid nearly the same until 150 meters downstream of the taper-point.

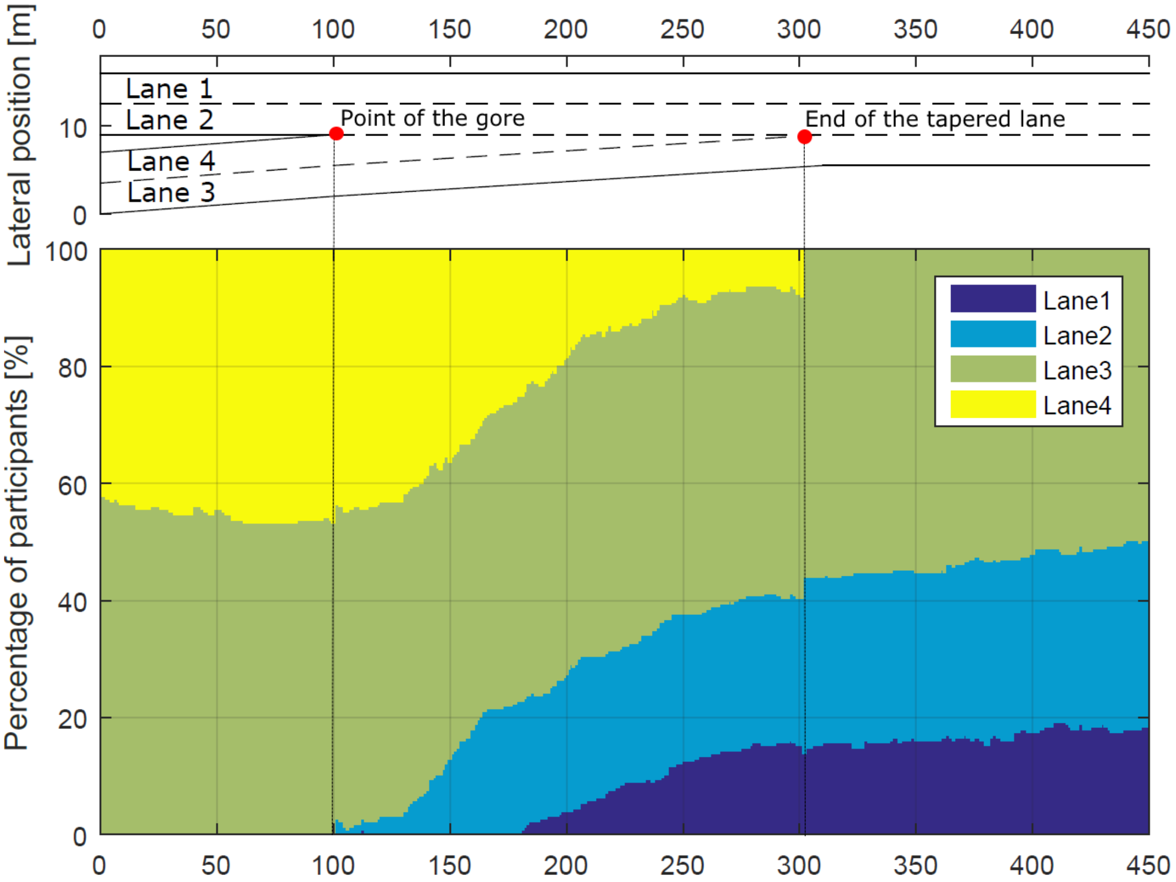


Figure 5.10: Participants' lane choice measured on all merging taper scenarios in the driving simulator, plotted as cumulative percentage.

Table 5.4: Participants' lane choice on all merging taper scenarios in the driving simulator, expressed in percentages.

Lane	**100 m upstream of point of the gore**	**point of the gore**	**taper-point**	**150 m downstream of the taper**
1	0%	0%	15%	18%
2	0%	0%	29%	32%
3	58%	53%	56%	50%
4	42%	47%	0%	0%

Figure 5.11 indicates the longitudinal location of each lane change sorted by each scenario. It can be seen that the most lane changes took place downstream of the point of the gore, in the first part of the tapered lane. On the standard geometric design (scenario 9), a small peak of lane changes can be seen around 200 meters upstream of the lane drop. It can also be seen that downstream of the lane drop on scenario 9, two more lane changes took place. In table **??** the number of lane changes on each scenario is given. In the experiment, the number of participants was not equal on each scenario. To overcome this, the total number of lane changes per scenario was divided by the number of participants on the particular scenario. Scenario 4, 5 and 7 are the three scenarios on which the number of lane changes was the lowest. These three scenarios do not have traffic conditions or road design in common. On scenario 2, 6 and 8 the number of lance changes is the highest. On all these scenarios, the taper-length is long. Regarding traffic volume and the percentage of heavy vehicles, these scenarios do not have conditions in common. From these findings it is suspected that a long taper-length caused more lane changes. However, this is contradicted by scenario 4 which has a long taper-length but the number of lane changes is low. The number of lane changes on merging tapers was slightly lower compared to the standard geometric design (1,44 against 1,48 lane changes).

Table 5.5: Average number of lane changes per scenario per participant, measured in the driving simulator.

Scenario	1	2	3	4	5	6	7	8	9
Nr. of lane changes per participant	1,20	1,84	1,42	1,11	1,17	1,81	0,81	2,17	1,48

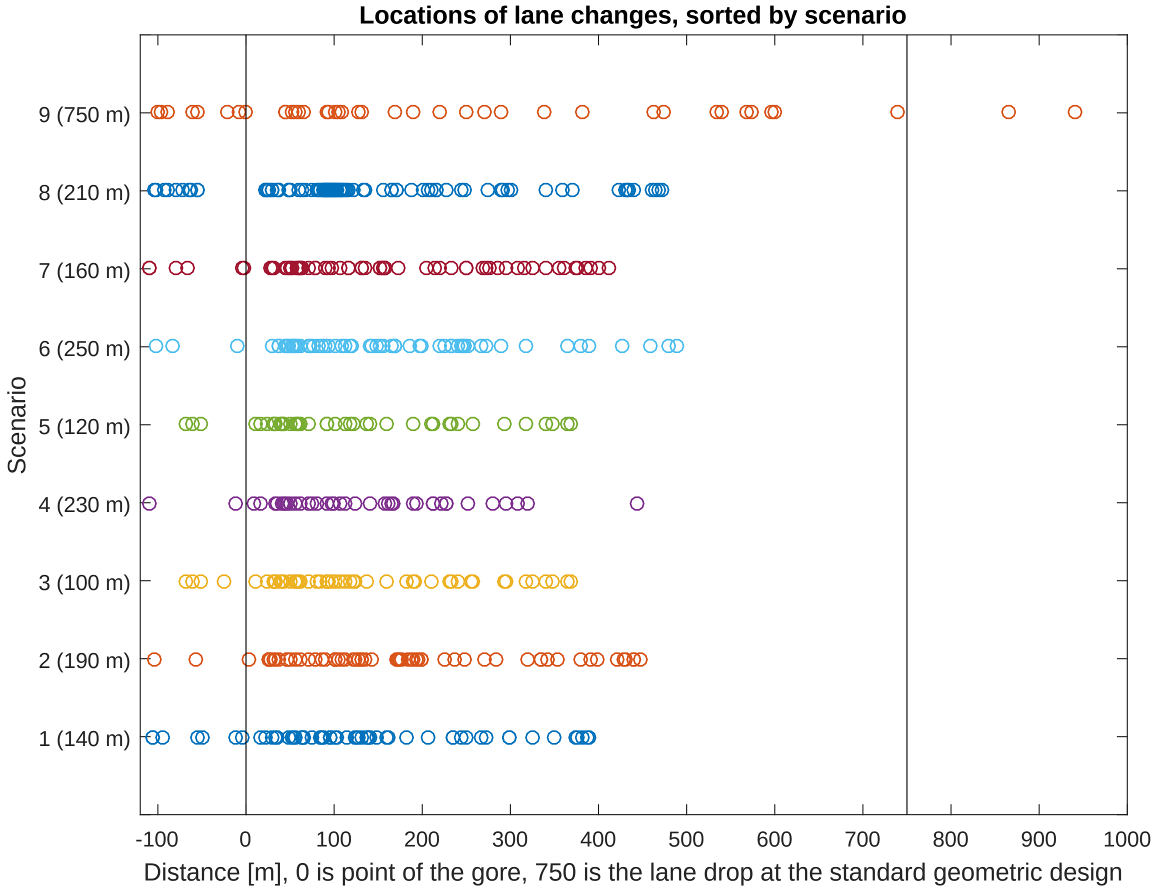
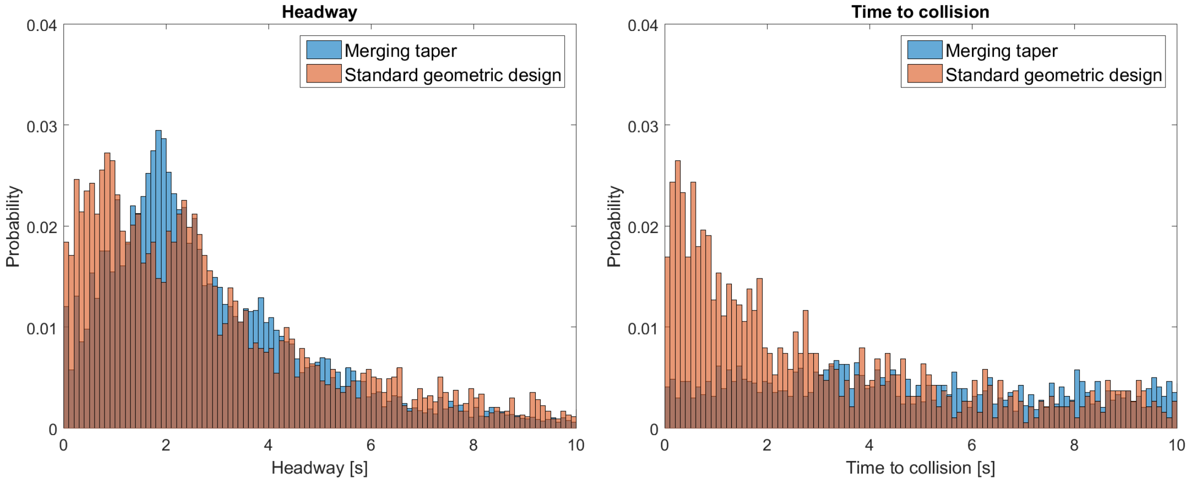


Figure 5.11: Lane change locations (in longitudinal direction) measured in the driving simulator, sorted by scenario.

5.3.2. MERGING TAPERS VERSUS STANDARD GEOMETRIC DESIGN

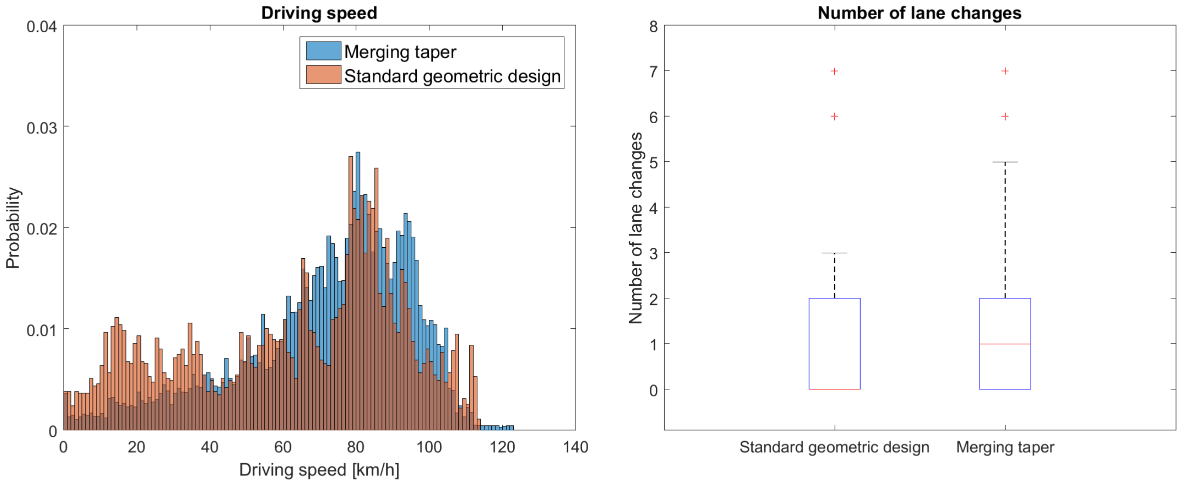
The driving behaviour on merging tapers and the standard geometric design was compared using the output variables time headway, time to collision, driving speed and the number of lane changes. In order to do so, first the measurements on both road designs were compared by means of graphs. Besides, a paired samples t-test was used to determine whether there was a statistically significant mean difference between the measured values when participants drove on the standard geometric design compared to a merging taper. More information about why this statistical test was chosen is discussed in more depth in section 4.5.

The measurements from both the standard geometric design and merging taper are graphically displayed in figure 5.12. In the two histograms, all collected data points (four data points per simulation second) were taken into account, and values smaller than 10 s were plotted since these were most relevant in terms of road safety. In the histogram with the time headway measurements, it can be seen that the distribution of the standard geometric design was right-skewed compared to the distribution of the merging tapers. This indicates that the probability on small time headway values on the standard geometric design is high compared to a merging taper, and thus the probability on high-severity conflicts on the standard geometric design is relatively high. This points in the direction that the road safety on merging tapers is high compared to the standard geometric design. The same pattern can be seen for the time to collision measurements; the probability on small time to collision values on the standard geometric design is high compared to a merging taper, and thus the probability on high-severity conflicts on the standard geometric design is relatively high. In the driving speed histogram in figure 5.12 it can be seen that the driving speed on the standard geometric design was more distributed compared to merging tapers, which indicates relatively low road safety on the standard geometric design. In this boxplot in figure 5.12, a boxplot with the number of lane changes per participant can be seen. It can be seen that the median of the number of lane changes was higher on merging tapers compared to the standard geometric design, which indicates relatively low road safety on merging tapers. However, the average number of lane changes per participant was more distributed on the standard geometric design compared to the merging taper. The median for the average number of lane changes on the standard geometric design was equal to zero, but there were also outliers on six and seven lane changes.



(a) Time Headway

(b) Time To Collision



(c) Driving speed

(d) Number of lane changes per participant

Figure 5.12: Graphs of time headway, time to collision, driving speed and number of lane changes measured on the merging taper scenarios and standard geometric design scenario. Regarding the boxplot: IQR is the middle 50% of the data, whiskers extend to maximum 1,5*IQR.

In order to analyse the data in more detail, a paired samples t-test was performed. The results can be found in table 5.6. In this table, the mean and standard deviation of all measurements are given, and also the p-value (the level of statistical significance) is given which indicates the level of evidence against the null hypotheses. A p-value smaller than 0,05 indicates strong evidence against the null hypothesis, so the null hypotheses will be rejected. For each variable, the null hypothesis was that the mean difference between the measurements on merging tapers and the standard geometric design is equal to zero. The alternative hypotheses was that there is a difference between the values measured on the standard geometric design and the merging taper. The t-value measures the size of the difference relative to the variation in the data. The greater the magnitude of the t-value, the greater the evidence against the null hypothesis. From the results in table 5.6, it can be seen that the mean time headway was greater on merging tapers (5,74 s ±3,62 s) compared to the standard geometric design (4,77 s ±2,98 s). The mean time to collision was higher on merging tapers (17,72 s ±6,39 s) compared to the standard geometric design (12,51 s ±10,13 s). These differences could already be expected from the histograms presented in figure 5.12. From table 5.6 it can be seen that the mean driving speed was greater on merging tapers (75,31 km/h ±7,06 km/h) compared to the standard geometric design (68,52 km/h ±20,45 km/h). It can be seen in figure 5.12 that the average number of lane changes per participant was more distributed on the standard geometric design compared to the merging taper. The median for the average number of lane changes on the standard geometric design was equal to zero, but there were also outliers on six and seven lane changes. The mean of the number of lane changes was lower on merging tapers (1,39 ±0,81) compared to the standard geometric design (1,48 ±2,17). However, the results from the paired samples t-test in table 5.6 show that none of the mean differences between merging tapers and the standard geometric design were statistically significant. Therefore, the null hypotheses for all output variables are accepted and the alternative hypotheses are accepted.

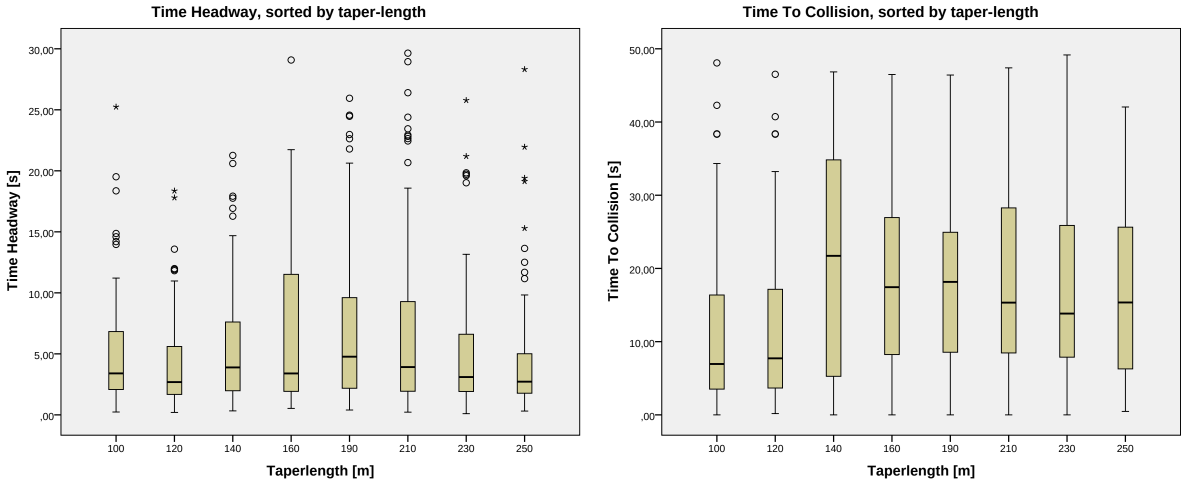
Table 5.6: Results of a paired sampled t-test, to compare the driving simulator's measurements on the merging tapers and the standard geometric design.

		Mean	**St. dev.**	**Mean diff.**	**t-value**	**p-value**
Time Headway [s]	Standard design	4,77	2,98	0,97	0,92	0,37
	Merging taper	5,74	3,62			
Time To Collision [s]	Standard design	12,51	10,13	5,21	1,98	0,06
	Merging taper	17,72	6,39			
Driving speed [km/h]	Standard design	68,52	20,45	6,78	1,49	0,15
	Merging taper	75,31	7,06			
Number of lane changes	Standard design	1,48	2,17	-0,09	-0,23	0,82
	Merging taper	1,44	0,81			

5.3.3. FACTORS' EFFECT: GRAPH-BASED ANALYSIS

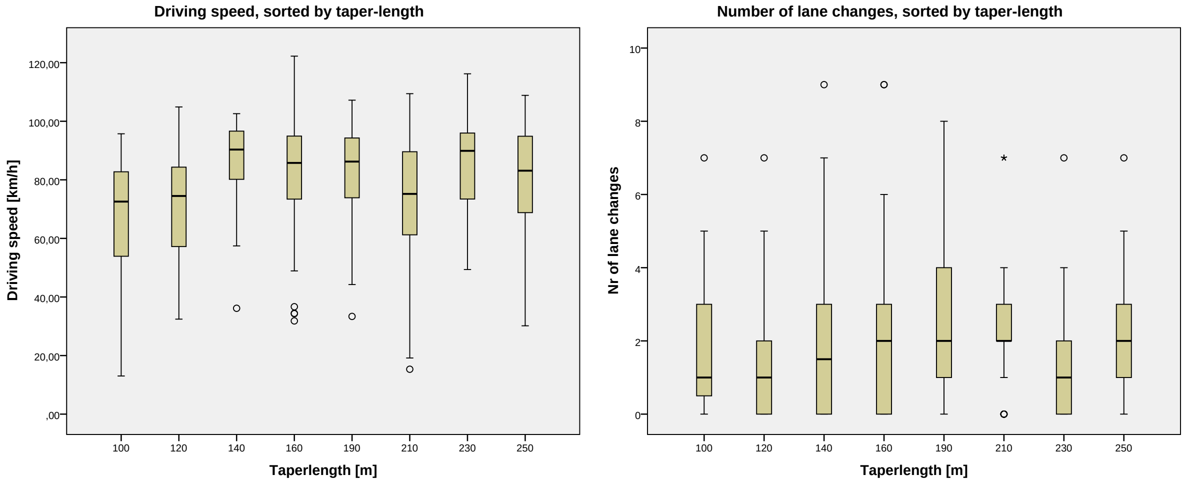
This subsection analyses the effect of the factors (taper-length, traffic volume, % of heavy vehicles) on the output variables (time headway, time to collision, driving speed, number of lane changes) visually using box plots. For each factor's level a box plot with the output data is plotted in the same figure. The box plots were ordered from small factor's level to large factor's level, to find possible trends in the data. The box represents the middle 50% of the measurements and is referred to as the inter-quartile range (IQR). The median marks the mid-point of the data and is shown by the line that divides the boxed in two. The upper and lower whiskers extend to 1,5 times the IQR or, if no measurement is in that range, to the minimum or maximum values. Data points which are represented as points were outliers which do not fall in the whiskers. Data points which are represented as stars were extreme outliers, which means that the values were more than three times the height of the box above the maximum value.

Taper-length The output variables time headway, time to collision, driving speed and average number of lane changes were plotted separately for each scenario in figure 5.13, and were sorted by taper-length. It can be seen that time headway values are less distributed on scenarios with a short or long taper-length compared to scenarios with a middle-long taper-length. In general it can be seen that the greatest time headway values are measured on merging tapers with a middle-long taper-length. Regarding time to collision it can be seen that the box and median of the scenarios with the shortest taper-length were lower compared to the other merging tapers, which was expected in the hypothesis. However, the box and median of the scenario with the third-shortest taper-length was high compared to the scenarios. This was not expected in the hypotheses, but might be explained because on this scenario the traffic volume on both roadways is low and no heavy vehicles are present. These factors were expected to account for the results on the scenario discussed above. It can be seen that the driving speed was the lowest on the two scenarios with the shortest taper-lengths. This points in the direction that road safety on merging tapers is relatively high if the taper-length is short, which was not expected in the hypothesis. On the rest of the scenarios, the driving speed was relatively high except for the scenario with a taper-length of 210 m. It can be seen that on scenarios with a long taper-length, lane changes occurred more often compared to scenarios with a short taper-length. However, on merging tapers with a long taper-length, data is collected over a longer distance compared to merging tapers with a short taper-length. The number of lane changes in figure 5.13 is not discounted with the taper-length. Therefore, it is not possible to indicate a trend between the number of lane changes and the taper-length. From the results discussed above it can be stated that no clear trend for the taper-length was found for each of the output variables.



(a) Time headway

(b) Time to collision

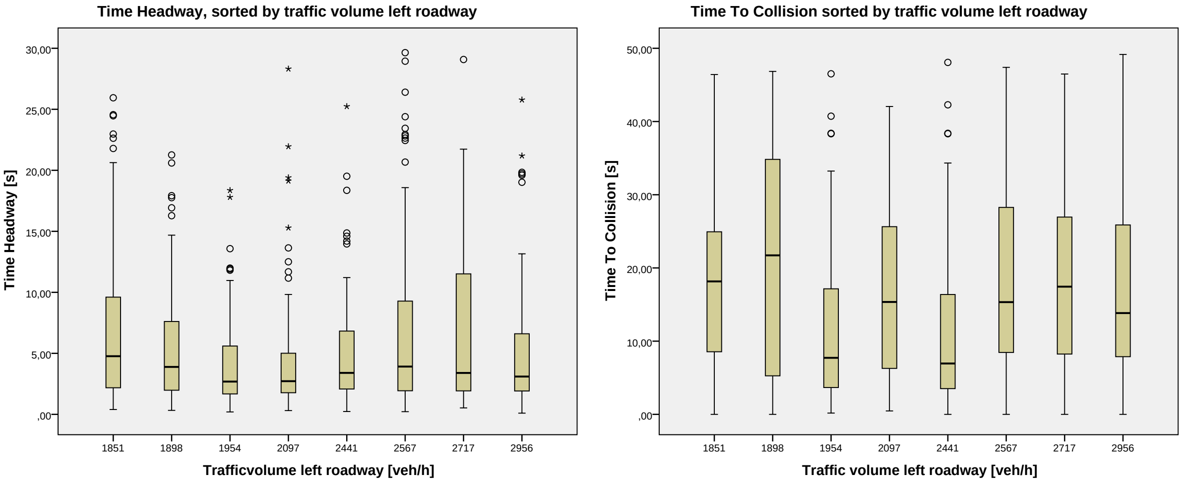


(c) Driving speed

(d) Number of lane changes per participant

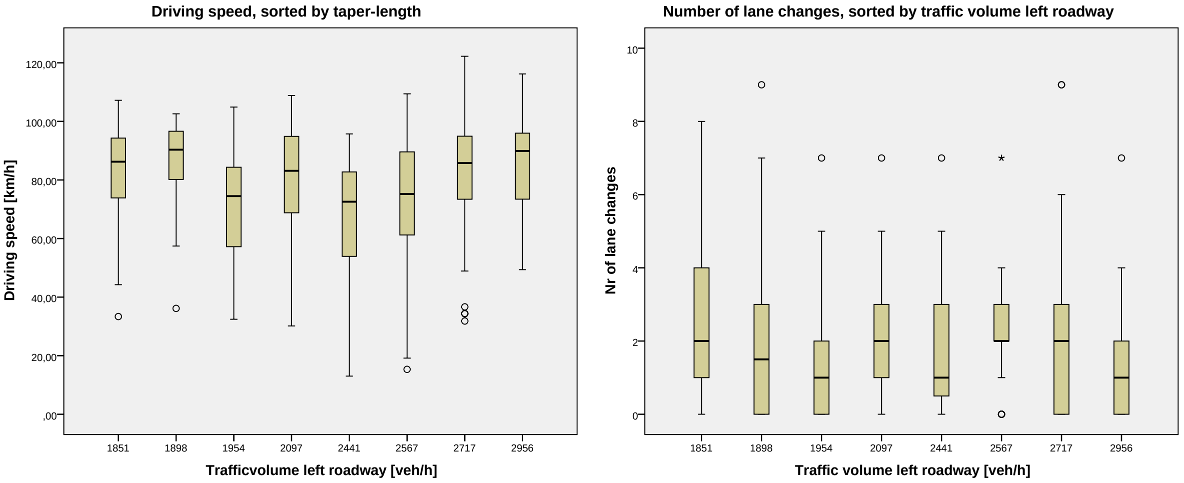
Figure 5.13: Boxplots of time headway, time to collision, driving speed and number of lane changes measured on merging tapers in the driving simulator, sorted by taper-length. IQR is the middle 50% of the data, whiskers extend to maximum 1,5 * IQR.

Traffic volume on the left roadway The output variables time headway, time to collision, driving speed and number of lane changes were plotted separately for each scenario in figure 5.14, and were sorted by the traffic volume on the left roadway. It can be seen that the smallest time headway values were found on the scenarios with a middle-range traffic volume on the left roadway. In scenarios with the highest time headway values, the traffic volume on the left roadway was either low or a high. As small time headway values indicate low road safety, the results point in the direction that road safety on merging tapers with a middle-range traffic volume on the left roadway is low. This was not expected in the hypothesis since it was expected that the higher the traffic volume, the smaller time headway values and the lower road safety. It can be seen that the smallest time to collision values were measured on scenarios with an middle-range traffic volume on the left roadway (1954 veh/h and 2441 veh/h). For time to collision values the same holds as for the time headway values; the smallest time to collision values were expected on scenarios with a high traffic volume on the left roadway. It can be seen that the driving speed was slightly lower on scenarios with a middle-range traffic volume on the left roadway, compared to scenarios with a low or high traffic volume on the left roadway. This result points in the direction that road safety on merging tapers with a middle-range traffic volume on the left roadway is high, which was expected on scenarios with a low traffic volume on the left roadway. It can be seen that zero lane changes per participant were made on scenarios with either a low or a high traffic volume on the left roadway. From the results discussed above it can be stated that no clear trend for the traffic volume on the left roadway is found for each of the output variables.



(a) Time Headway

(b) Time To Collision

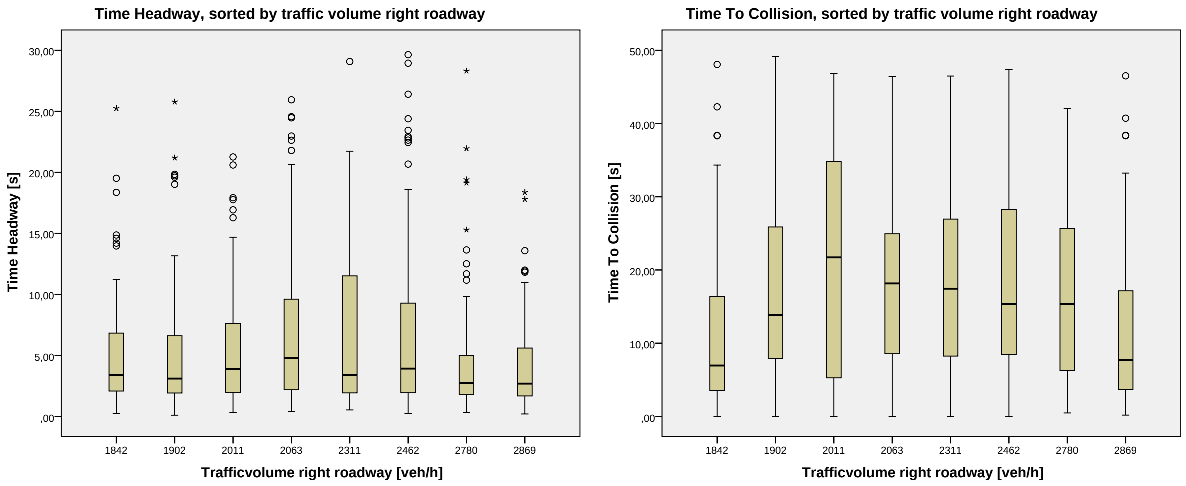


(c) Driving speed

(d) Number of lane changes per participant

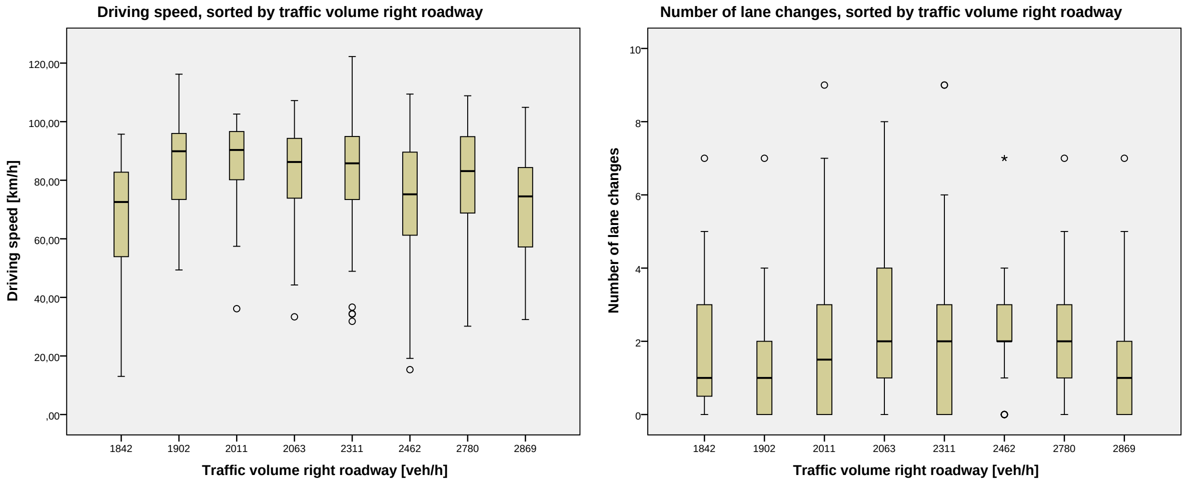
Figure 5.14: Boxplots of time headway, time to collision, driving speed and number of lane changes measured on merging tapers in the driving simulator, sorted by the traffic volume on the left roadway. IQR is the middle 50% of the data, whiskers extend to maximum 1,5 * IQR.

Traffic volume on the right roadway The output variables time headway, time to collision, driving speed and number of lane changes were plotted separately for each scenario in figure 5.15, and were sorted by the traffic volume on the right roadway. Regarding time headway measurements it can be seen that the smallest values were found on scenarios with either a low traffic volume on the right roadway or a high traffic volume on the right roadway. The highest time headway were measured on scenarios with a mid-range traffic volume on the right roadway. A similar pattern can be seen for the time to collision measurements, as the smallest time to collision values were measured on scenarios with either low or high traffic volumes. The highest time to collision values are measured on scenarios with a mid-range traffic volume on the right roadway. The time headway and time to collision values point in the direction that road safety on merging tapers with a mid-range traffic volume on the right roadway is low. It can be seen that the driving speed was the highest on scenarios with a mid-range traffic volume on the right roadway. The driving speed was the lowest on the scenarios with either a low or a high traffic volume on the right roadway. It can be seen that the number of lane changes is low on both scenarios with a high traffic volume and a low traffic volume. However, it was expected in the hypothesis that the number of lane changes would be the highest on merging tapers with a high traffic volume on the right roadway. From the results discussed above it can be stated that no clear trend for the traffic volume on the right roadway is found for each of the output variables.



(a) Time Headway

(b) Time To Collision

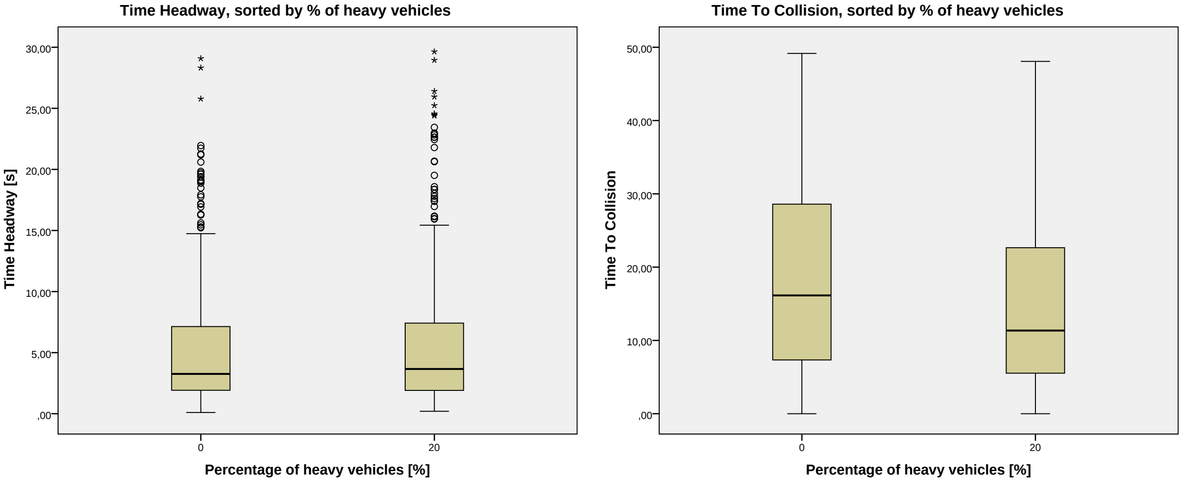


(c) Driving speed

(d) Number of lane changes per participant

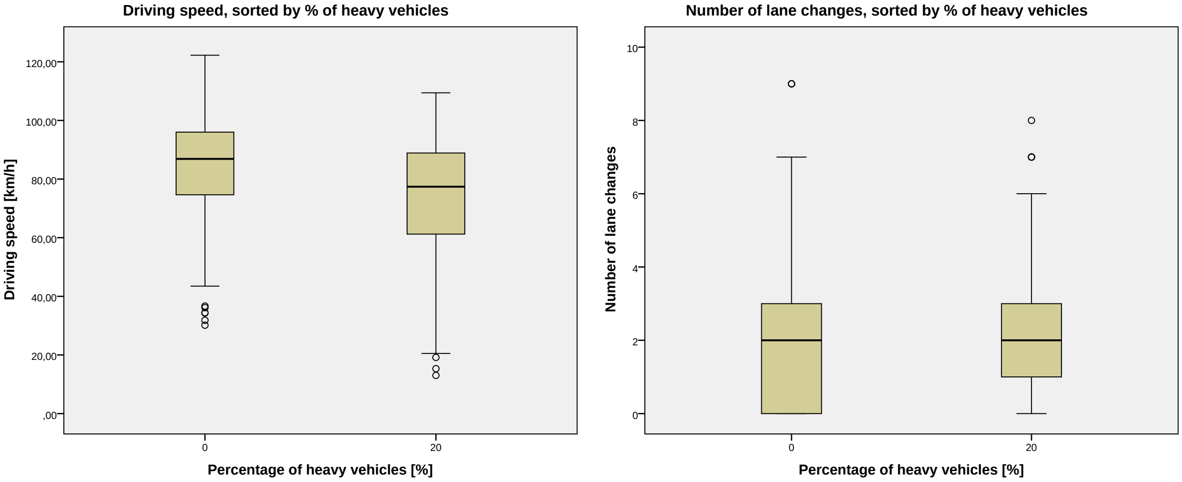
Figure 5.15: Boxplots of time headway, time to collision, driving speed and number of lane changes measured on merging tapers in the driving simulator, sorted by the traffic volume on the right roadway. IQR is the middle 50% of the data, whiskers extend to maximum 1,5 * IQR.

Percentage of heavy vehicles The factor percentage of heavy vehicles had only two levels in the experimental design. As a result, the graphs with the data output contains only two box plots. The output variables time headway, time to collision, driving speed and number of lane changes were plotted for both levels of percentage of heavy vehicles in figure 5.16. It can be seen that the time headway values were similar on scenarios with or without heavy vehicles. This was not expected, since it was expected that on scenarios with 20% heavy vehicles the time to collision values would be low and thus the road safety would be low. A difference was found for time to collision values; time to collision values were smaller if the percentage of heavy vehicles was high. This result was expected in the hypothesis, since it points at the direction that road safety at merging tapers with a high percentage of heavy vehicles is low. It can be seen that the driving speed was lower on scenarios with a high percentage of heavy vehicles. This points at the direction that road safety on merging tapers with a high percentage of heavy vehicles is high, which was not expected in the hypothesis. This result might have been the result of the fact that heavy vehicles often drove slow compared to passenger vehicles. It is possible that participants were not able to overtake a relative slow heavy vehicles, which resulted in low driving speeds. It can be seen that the median of the average number of lane changes per participant is similar for both percentages of heavy vehicles. However, it can be seen that the box of the scenarios with 0% heavy vehicles reaches much lower compared to the box of the scenarios with 20% heavy vehicles. So, lane changes were made more often on scenarios with 20% percentage of heavy vehicles compared to scenarios with 0% heavy vehicles. This points in the direction that road safety on merging tapers with a high percentage of heavy vehicles is low, which was expected in the hypothesis.



(a) Time Headway

(b) Time To Collision



(c) Driving speed

(d) Number of lane changes per participant

Figure 5.16: Boxplots of time headway, time to collision, driving speed and number of lane changes measured on merging tapers in the driving simulator, sorted by the percentage of heavy vehicles. IQR is the middle 50% of the data, whiskers extend to maximum 1,5 * IQR.

5.3.4. FACTORS' EFFECT: LINEAR MIXED MODEL

No trends were found for each of the factors in the analysis in subsection 5.3.3. This might have been the result of the experimental design, in which the factor's levels were different in each scenario. So if a factor's level differed between two scenarios, the level of the other factors also changed. For example, if the taper-length differed between two scenarios, the traffic volume on the right roadway had changed. In order to go into more detail in the data, a Linear Mixed Model was estimated to analyse the main effect of the factors on the output variables, as well as the interaction effects. Linear Mixed Models were discussed in more detail in section 4.5. The effect of taper-length, traffic volume on the left roadway, traffic volume on the right roadway and the percentage of heavy vehicles on the output variables time headway, time to collision, driving speed and number of lane changes per participant was analysed. After that, the data was split for each segment (see figure 4.11) to analyse the effect of the different segments on the output variables is analysed. Furthermore the 2nd order effects were studied with a Linear Mixed Model, to find interaction effects. The up-following paragraph discusses the LLM build-up in this specific study, after which the results are discussed.

Linear Mixed Model build up The LLM analysis was performed in SPSS by clicking to Analyze → Mixed Models → Linear. The subject variable and repeated variable for the model were specified. The participant is defined as subject. Multiple observations were done for the same participant on different scenarios. Therefore, the scenario was defined as a repeated variable. The Repeated Covariance Type was also defined in this dialogue window which refers to the covariance structure which was used to model the fact that the errors of repeated measurements on individuals were potentially correlated (and therefore dependent). The covariance structure indicates how measurements on the different scenarios were related to each other. A covariance structure is a pattern in a covariance matrix which contains the variances and covariances associated with the output variables. Regarding this study, the covariance matrix contained the variance and covariance of output variables' values measured in the different scenarios. Several different covariance structures can be chosen, which all have a different pattern. In this study the first-order heterogeneous autoregressive (ARH(1)) covariance structure was chosen. This structure is a simple extension of the first-order autoregressive structure, and is commonly used [84]. The structure has heterogeneous variances, which means that the variance on each scenario may be different. This is a reasonable assumption, since for example the driving speed (figure 4.7) already has shown to have different variances over the different scenarios. The covariances in the ARH(1) structure decrease with the distance. This means that values which are measured next to each other were more correlated compared to values which are measured far away from each other. This makes sense in this study, since the measurements over distance were affected by for example external influences such as other vehicles. If a participant conflicted much with other vehicles, the measurements would be less correlated. Therefore, it was reasonable to assume that the covariance decreased over the distance. Based on the assumptions for variance and covariance, the ARH(1) covariance structure was chosen in the LLM.

In the second dialogue window, the dependent variable was defined which was an output variable such as time headway and time to collision. The independent variables were defined in the factors box or the covariates box, which were the taper-length, traffic volume on the left roadway, traffic volume on the right roadway and percentage of heavy vehicles. The percentage of heavy vehicles was entered in the factors box since this independent variable was a categorical predictor. The taper-length and traffic volume were entered in the covariates box since these independent variables were scale predictors. The factors and covariates which accounted for the fixed effect, accounted for the entire population (participant group). Under the "fixed" button, the factors and covariates were defined as a main effect on the dependent variable. Under the "random" button, the "include intercept" box was checked. Excluding the intercept would have meant that it was assumed that the extrapolation of the rest of the data would cross the origin of the graph, which would not make sense in this study since a data point would be added that should not be there. Under the "subject groupings" header, the participants were added as a variable. They accounted for the random effects because each participant holds different characteristics which influenced the output variables. It is unimportant which covariance type was selected for the random effects, since no covariance type of random effects was included in the model (no covariance was present since only one random effect was specified).

In the next step of the analysis, the effect of the different segments from figure 4.11 on the output variables was studied. To do so, the segments were added as a independent variable in the estimation of the Linear Mixed Model. For this analysis the build-up of the model was slightly different than described above. The following changes were made: The scenario was added as a subject variable, instead of a repeated variable in the first model estimation. Because each participant drove over all segments on a scenario, the segment was added as a repeated measure. Besides, the segment is added as a factor because it was a categorical predictor, and was also added under the "fixed" button as a main effect since the effect of the segments on the output variables was analysed. The rest of the build-up was identical to the Linear Mixed Model build-up which was described earlier in this paragraph.

Results: main effects Output of the first Linear Mixed Model (LMM) can be seen in table 5.7. Regarding time headway it can be seen that the intercept on merging tapers with 20% heavy vehicles was 6,07 s with a standard error of 3,04 s, which is nearly significant with t(48,29) = 1,99, p = 0,05. Regarding the factor's estimates, none of the factors had a significant effect on time headway values.

Regarding time to collision it can be seen that the intercept on merging tapers with 20% heavy vehicles was 26,13 s with a standard error of 9,53 s. The intercept was statistically significant with t(59,45) = 2,55, p = 0,01. It can be seen that the factor percentage of heavy vehicles had a significant effect on time to collision values (t(59,45) = 2,55, p = 0,01). The estimate is positive which indicates a negative effect of heavy vehicles on time to collision values; on merging tapers with heavy vehicles the time to collision values were smaller. This means that the percentage of heavy vehicles on merging tapers has a negative effect on road safety, which was expected in the hypothesis. It can be seen that the factor traffic volume on the right roadway had a significant effect on time to collision values (t(46,17) = -2,12, p = 0,04). The estimate is negative which indicates a negative effect on time to collision values; on merging tapers with a high traffic volume on the right roadway the time to collision values were lower. This means that the traffic volume on the right roadway on merging tapers has a negative effect on road safety, which was expected in the hypothesis. The factors taper-length and traffic volume on the left roadway had no significant effect on time headway values.

Regarding the driving speed it can be seen that the intercept on merging tapers with 20% heavy vehicles was 109,38 km/h with a standard error of 10,36 km/h. The intercept was statistically significant with t(44,53) = 10,55, p < 0,01. It can be seen that the factor percentage of heavy vehicles had a significant effect on driving speed (t(87,67) = 5,10, p < 0,01). The estimate is positive which indicates a negative effect of heavy vehicles on driving speed values; on merging tapers with heavy vehicles the driving speed was low. This means that the percentage of heavy vehicles on merging tapers has a positive effect on road safety, which was not expected in the hypothesis. It can be seen that the factor taper-length had a significant effect on driving speed (t(72,61) = 2,35, p = 0,02). The estimate is positive which indicates a positive effect of taper-length on driving speed values; on merging tapers with a long taper-length the driving speed was high. This means that the taper-length has a negative effect on road safety, which was not expected in the hypothesis. It can be seen that the factor traffic volume on both the left and right roadway had a significant effect on driving speed (respectively t(89,76) = -3,85, p < 0,01 and t(36,37) = -3,17, p < 0,01). The estimates are negative which indicates a negative effect of the traffic volume on driving speed values; on merging tapers with a high traffic volume the driving speed was low. This means that the traffic volume has a positive effect on road safety, which was not expected in the hypothesis. As discussed above, all factor's effect on driving speed and road safety was not expected in the hypothesis. However, the effect of the driving speed on road safety is debatable, since the average driving speed is rather low compared to the speed limit. This can be seen in figure 5.7, knowing that the speed limit is 100 km/h.

Regarding the number of lane changes, no results were obtained from the linear mixed model. SPSS stated that convergence has not been achieved, and therefore the validity of the model fit is uncertain. In the remaining of the analysis, the data was splitted for the defined segments which can be seen in figure 4.11, in order find the effect of the different segments on the output variables. How the Linear Mixed Model build-up was changed compared to the first estimation, was explained in the previous paragraph.

Output of the second Linear Mixed Model estimation is presented in table 5.8. The intercept of time headway measurements on segment D with 20% heavy vehicles was 4,45 s with a standard error of 1,53 s. This intercept was statistically significant with t(210,24) = 2,91, p < 0,01. It can be seen that the estimates of time headway values on segments A, B and C were higher compared to segment D, and the differences are statistically significant. This indicates that the smallest time headway values were measured in segment D, which means that road safety is the lowest in segment D. However, this might have been the result of the assumption made in section 4.5, in which a predecessor is assumed at the end of the measurement area. The assumed vehicles were the nearest to the participant's vehicle in segment D, and therefore time headway was the smallest in that segment. The data seem to indicate a trend that taper-length has a negative effect on time headway values, which means that taper-length has a negative effect on road safety. This trend was

Table 5.7: Linear mixed model output of the output variable time headway, time to collision and driving speed measured on merging tapers in the driving simulator (first estimation).

	Estimate	**Std. error**	**df**	**t**	**Sig.**
Time headway [s]					
Intercept	6,07	3,04	48,29	1,99	0,05
% Heavy veh. = 0	-0,83	0,69	74,94	-1,19	0,24
% Heavy veh. = 20	0	0	-	-	-
Taper-length	-1,00e-3	6,06e-3	59,72	-0,17	0,87
Traffic volume left roadway	3,43e-4	7,75e-4	88,47	0,44	0,66
Traffic volume right roadway	-1,61e-3	6,06e-4	23,34	-0,74	0,46
Time to collision [s]					
Intercept	26,13	9,53	47,22	2,74	0,01
% Heavy veh. = 0	6,46	2,53	59,45	2,55	0,01
% Heavy veh. = 20	0	0	-	-	-
Taper-length	0,03	0,02	45,76	1,52	0,14
Traffic volume left roadway	-3,24e-3	2,84e-3	47,45	-1,14	0,26
Traffic volume right roadway	-3,62e-3	1,70e-3	46,17	-2,12	0,04
Driving speed [km/h]					
Intercept	109,38	10,36	44,53	10,55	<0,01
% Heavy veh. = 0	10,90	2,14	87,67	5,10	<0,01
% Heavy veh. = 20	0	0	-	-	-
Taper-length	0,05	0,02	72,61	2,35	0,02
Traffic volume left roadway	-0,01	2,92e-3	89,76	-3,85	<0,01
Traffic volume right roadway	-9,09e-3	2,93e-3	36,37	-3,17	<0,01

not expected in the hypothesis, and in addition the estimate of taper-length was not significant. None of the other factors had a significant effect on time headway values.

Regarding time to collision, it can be seen that the intercept of time to collision measurements on segment D with 20 % heavy vehicles was 25,19 seconds with a standard error of 9,66 seconds. This intercept was statistically significant with t(129,72) = 2,61, p = 0,01. It can be seen that the estimate of time to collision values on segment C was lower (-3,63 ±1,11) compared to segment D. The difference was statistically significant, t(165,36) = -3,28, p < 0,01. This indicates that the lowest time to collision values were measured on segment C, which means that the road safety is the lowest on segment C. It can be seen that the factor taper-length had a significant effect (t(128,89) = 2,32, p = 0,02) on time to collision measurements. The estimate is positive which indicates that the taper-length has a positive effect on time to collision values; on merging tapers with with a long taper-length the time to collision values were high. This means that the taper-length has a positive effect on road safety, which was expected in the hypothesis.

Regarding the driving speed, it can be seen that the intercept of driving speed measurements on segment D with 20 % heavy vehicles was 80,97 km/h with a standard error of 8,97 km/h. This intercept was statistically significant with t(246,94) = 9,02, p < 0,01. The driving speed on segment A and segment B was significantly higher compared to segment D. A similar pattern was found in the speed plots in figure 5.7. It can be seen that the factor percentage of heavy vehicles had a significant effect on driving speed (t(223,30) = 3,37, p < 0,01). The estimate is positive which indicates a negative effect of heavy vehicles on driving speed values; on merging tapers with heavy vehicles the driving speed was low. This means that the percentage of heavy vehicles on merging tapers has a positive effect on road safety, which was not expected in the hypothesis. None of the remaining factors had a significant effect on driving speed. However, the effect of the driving speed on road safety is debatable, since the average driving speed is rather low compared to the speed limit. This can be seen in figure 5.7, knowing that the speed limit is 100 km/h.

It can be seen that the intercept of the number of lane changes per participant on segment D with 20 % heavy vehicles is 0,23 lane changes with a standard error of 0,10. This intercept was significant with t(439,49) = 2,30 p = 0,02, thus the intercept was statistically significant. It can be seen that the average number of lane changes per participant is significantly lower on segment A compared to segment D. On segment B and segment C, the average number of lane changes is higher compared to segment D. This result could have been expected in the hypothesis, since the tapered lane was situated on segment B and C. Participants who drove on this lane, must have changed lane in these segments. None of the other factors had a significant effect on the number of participants per participant.

Table 5.8: Linear mixed model output of the output variable time headway, time to collision, driving speed and number of lane changes measured on merging tapers in the driving simulator (second estimation).

	Estimate	**Std. error**	**df**	**t**	**Sig.**
Time headway [s]					
Intercept	4,45	1,53	210,24	2,91	<0,01
% Heavy veh. = 0	0,09	0,32	190,73	0,28	0,78
% Heavy veh. = 20	0	0	-	-	-
Segment A	6,00	0,63	229,92	9,50	<0,01
Segment B	3,04	0,38	261,32	7,91	<0,01
Segment C	0,92	0,28	250,64	3,25	0,01
Segment D	0	0	-	-	-
Taper-length	-0,01	0,00	200,87	-1,94	0,05
Traffic volume left roadway	8,38e-5	0,00	201,31	0,20	0,84
Traffic volume right roadway	-8,11e-5	0,00	205,51	-0,18	0,86
Time to collision [s]					
Intercept	25,19	9,66	129,72	2,61	0,01
% Heavy veh. = 0	2,34	2,01	126,57	1,16	0,25
% Heavy veh. = 20	0	0	-	-	-
Segment A	0,72	1,63	198,30	0,44	0,66
Segment B	-2,19	1,35	216,77	-1,61	0,11
Segment C	-3,63	1,11	165,36	-3,28	<0,01
Segment D	0	0	-	-	-
Taper-length	0,05	0,02	128,89	2,32	0,02
Traffic volume left roadway	2,85e-3	0,00	127,51	-1,06	0,29
Traffic volume right roadway	3,68e-3	0,00	126,60	-1,39	0,17
Driving speed [km/h]					
Intercept	80,97	8,97	246,94	9,02	<0,01
% Heavy veh. = 0	6,35	1,89	223,30	3,37	<0,01
% Heavy veh. = 20	0	0	-	-	-
Segment A	12,13	1,04	459,96	11,64	<0,01
Segment B	6,51	1,01	558,64	6,44	<0,01
Segment C	-0,07	0,86	383,37	-0,08	0,94
Segment D	0	0	-	-	-
Taper-length	0,02	0,02	237,53	0,81	0,42
Traffic volume left roadway	7,78e-4	2,63e-3	237,68	-0,32	0,75
Traffic volume right roadway	4,66e-3	0,02	242,00	-1,77	0,08
Number of lane changes [-]					
Intercept	0,23	0,10	439,49	2,30	0,02
% Heavy veh. = 0	0,03	0,02	397,01	1,35	0,18
% Heavy veh. = 20	0	0	-	-	-
Segment A	-0,15	0,03	320,07	-4,74	<0,01
Segment B	0,01	0,04	420,99	0,20	0,85
Segment C	0,07	0,04	301,13	1,65	0,10
Segment D	0	0	-	-	-
Taper-length	8,23e-5	0,00	397,01	0,38	0,70
Traffic volume left roadway	-2,11e-5	2,68e-5	397,01	-0,79	0,43
Traffic volume right roadway	-7,31e-6	2,83e-5	397,01	-0,26	0,80

Results: interaction The next step in the analysis was to find interaction effects, which holds that each combination of factor levels may have a different effect on the dependent variable. For example, the effect of taper-length on time to collision may change for different levels of traffic volume. For each level of traffic volume, the slope which indicates the effect of taper-length on time to collision may be different.

A statistically significant interaction was found between percentage of heavy vehicles and taper-length on time to collision (t(69,62) = -4,25, p < 0,01). The data output from SPSS can be seen in figure 5.9. The estimate had a negative sign if 0% heavy vehicles are present, which indicates that the effect of taper-length on time to collision was smaller if no heavy vehicles were present. This means that the effect of taper-length on road safety is smaller if no heavy vehicles are present. This interaction makes sense, because it may be reasoned that if heavy vehicles are present, relative much space is blocked on a merging taper. In addition to a relative short taper-length, this can result in less space for merging manoeuvres, which can result in relative small time to collision values.

Table 5.9: Linear mixed model output including interaction term between percentage of heavy vehicles and taper-length, for the output variable time to collision measured on merging tapers in the driving simulator.

Time to collision [s]	**Estimate**	**Std. error**	**df**	**t**	**Sig.**
Intercept	16,98	8,95	65,89	1,90	0,062
% Heavy veh. = 0	35,06	7,17	48,52	4,99	<0,01
% Heavy veh. = 20	0	0	-	-	-
Taper-length	0,07	0,02	51,84	2,90	<0,01
Traffic volume left roadway	-1,78e-3	2,62e-3	59,52	-0,68	0,50
Traffic volume right roadway	-2,87e-3	1,63e-3	54,54	-1,76	0,08
[% Heavy vehicles = 0] * Taper-length	-0,15	0,04	69,62	-4,25	<0,01
[% Heavy vehicles = 20] * Taper-length	0	0	-	-	-

5.3.5. QUESTIONNAIRE AFTER THE DRIVING SIMULATOR EXPERIMENT

More information on the driving simulator realism was collected in the second questionnaire, which was conducted after the driving simulator experiment. As discussed in chapter 2, physical validity and behavioural validity were important in determining the driving simulator's realism. In the questionnaire, statements were presented which gave more information on the driving simulator's validity. Participants indicated whether they agreed or not with the statements, by answering on a 5-point Likert scale. Indicating 1 was equal to strongly disagree and 5 was equal to strongly agree. An overview of the questionnaire including all responses is given in appendix F, and the most important results are given in figure 5.17.

From the questionnaire's results it was found that participants experienced the road environment as realistic. For example, on the statement "The roadway and roadway traffic system seemed natural", 51,2% agreed and 24,4% strongly agreed. On the statement "Events which occurred during the drive seemed realistic", participants were less positive; 7,3% strongly agreed and 34,1% agreed on this statement, as 34,1% neither agreed or disagreed, 19,5% of the participants disagreed and 4,9% strongly disagreed. On the statement "The virtual environment seemed consistent with my real world experiences", 14,6% agreed and 36,6% neither agreed nor disagreed, 31,7% of the participants disagreed and 17,1% strongly disagreed.

It was found that participants did not experienced the characteristics (e.g. acceleration, steering) of the driving simulator vehicle as a real life vehicle's characteristics. On the statement "the movement of the vehicle seemed natural", 22% agreed and 29,3% neither agreed nor disagreed. Another 29,3% disagreed with this statement, and 19,5% strongly disagreed. On the statement "The vehicle responded to my actions in a way I expected", 14,6% agreed, 36,6% neither agreed or disagreed, 31,7% disagreed and 17,1% strongly disagreed. 31,7% agreed on the statement "The vehicle I drove behaved in a realistic way", 17,1% neither agreed nor disagreed and 51,2% disagreed. Of all participants, 34,1% agreed on the statement "The actions I performed in the car seemed consistent with the real world", 36,6% neither agreed nor disagreed, 22% disagreed and 7,3% strongly disagreed. The result of all statements might be summarized by the statement "I made driving errors that I don't make in real driving". 82,9% of the participants strongly agreed with this statement, as 14,6% agreed.

From the results stated above it was concluded that the participants' driving behaviour in the driving simulator did not reflect their real world driving behaviour. Based on the answered statements, physical validity of the driving simulator was not assured. Besides, it was concluded that driving simulator's behavioural validity was low, which was mainly illustrated by the statement "I made driving errors that I don't make in real driving". As a result of these two findings, it was concluded that the participant's driving behaviour in the driving simulator was different from real life driving behaviour. This conclusion must be taken into account when interpreting the other results and conclusions which were derived from the driving simulator study.

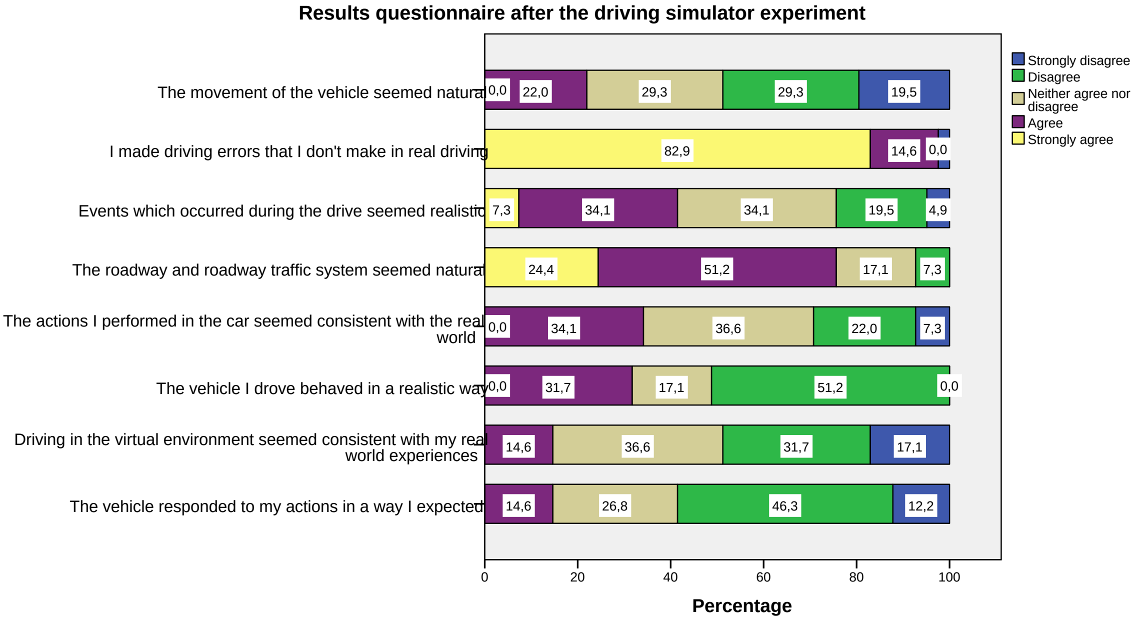


Figure 5.17: Results from the questionnaire which is performed after the driving simulator experiment.

5.4. FINDINGS

Several findings were made throughout the report, on the basis of the performed study. In order to get a good picture of the main findings, these area summarized below.

Literature study revealed that only one study has been performed on the road safety of Dutch merging tapers. The study of Grontmij [2] concluded that a large part of the road users who approach the merging taper on the right roadway, perceive the tapered lane as unsafe and therefore choose the rightmost lane. Multiple experts in the field compiled a list of 35 Dutch merging tapers, of which a large share had not been designed according to the design guidelines from the ROA [21]. In further literature research in both Dutch and foreign design guidelines, no underpinning was found for the presumption that a merging taper is unsafe compared to the standard geometric design. Besides, no underpinning was found for the merging taper's design guidelines which are stated in the ROA [21]. Design guidelines for similar foreign road designs are neither underpinned. A German road design which is similar to the Dutch merging taper is no longer applied after 1976 due to a high number of accidents on these locations.

Accident analysis was the first method which was used to measure "objective" road safety on merging tapers. The analysis was performed using accidents that have been registered between 2010 and 2013 on eight representative merging tapers. On these locations, the driving behaviour was not influenced by factors other than a standard merging taper design itself. For example, no outstanding buildings were present in the surrounding, as well as other discontinuities which might influenced the driving behaviour and thus road safety. It was found that most accidents occurred during peak hour, which indicates that the number of accidents is high if the traffic volume is high. This points in the direction that traffic volume has a negative effect on road safety; the higher traffic volume, the lower road safety. No trend was found between the number of accidents and the taper-length. The relation between the number of accidents and the percentage of heavy vehicles was not studied because the traffic composition was not found in the data. It was found that most of the severe accidents occurred over the weekend. Furthermore it was found that the quality of the accident data is poor, since multiple accidents were not registered or were registered inaccurately and incompletely.

A **questionnaire** was performed to measure the subjective road safety of merging tapers compared to the standard geometric design. It was found that 100% of the participants were familiar with the geometric design of a merging taper, and 97,6% of the participants were familiar with the standard geometric design. Of the participants which were familiar with both geometric designs, a greater part (65,9%) stated they will feel safer on the standard geometric design compared to a merging taper. 19,5% will feel safer on a merging taper, and the rest (14,6%) will feel equally safe on both geometric designs. Based on these results, road safety on merging tapers was considered low compared to the standard geometric design.

In a **driving simulator experiment** the road safety on merging tapers was compared to the standard geometric design. This was done by measuring driving behaviour using vehicle trajectories. Road safety was indicated by calculating surrogate safety measures such as time headway, time to collision, driving speed and number of lane changes. Multiple merging taper scenarios were integrated in the experiment to measure the effect of taper-length, traffic volume on the left roadway, traffic volume on the right roadway and % of heavy vehicles on driving behaviour and thus road safety.

The participants' average speed 110 meters upstream of the point of the gore of the merging tapers was 88,3 km/h, which was considered low if the maximum speed of 100 km/h was taken into account. The average driving speed decreased to 73,9 km/h at the taper-point. Downstream of the taper-point the average driving speed increased again. The standard deviation of driving speed measurements increased towards the taper-point, after which it decreased again downstream of the tapered lane. The standard deviation of driving speed measurements point in the direction that the road safety on merging tapers is the lowest around the taper-point. The low average driving speed around the taper-point can be explained by the location of the braking manoeuvres which mainly took place towards the end of the tapered lane. Braking manoeuvres on merging taper scenarios were concentrated just downstream of the point of the gore, and braking manoeuvres on the standard geometric design were concentrated just upstream of the lane drop. The average number of braking manoeuvres per participant on merging tapers is 58% lower (0,87 versus 2,09) compared to the standard geometric design.

It was found that 100 m upstream of the point of the gore 58% of the participants who approached on the right roadway, drove on the right-most lane. This percentage decreased slightly to 53% at the point of the gore. Directly downstream of the point of the gore participants started merging to the lane on the left side of the tapered lane. Around 180 m downstream of the point of the gore the first participant merged to the most-left lane of the roadway. At the taper-point, 15% merged to the leftmost lane as 56% drove on the rightmost lane and 29% drove on the middle lane. 150 meters downstream of the taper-point 50% drove on the rightmost lane, as the percentage on the other two lanes both increased with 3%.

The time headway, time to collision, driving speed and number of lane changes measurements on merging tapers were compared with the standard geometric design to compare the road safety of both road designs. Graphs were analysed, and it was determined whether the mean difference was statistically significant with the paired samples t-test. None of the mean differences were statistically significant, and therefore it can not be said whether merging tapers are more or less safe compared to the standard geometric design.

In the remaining of the study, the effect of the taper-length, traffic volume on the left roadway, traffic volume on the right roadway and percentage of heavy vehicles on the output variables was studied. Data was plotted in box plots for each individual scenario, and sorted from low level factors to high level factors in order to find trends. No trend was found for each of the factors. A Linear Mixed Model was estimated to analyse the factors' effect on the output variables. First, a model was estimated with the independent variables taper-length, traffic volume on the left roadway, traffic volume on the right roadway and percentage of heavy vehicles. It was found that none of the factors had a significant effect on time headway measurements. Traffic volume on the right roadway had a negative significant effect on time to collision values, which indicates that time to collision values on merging tapers with a high traffic volume on the right roadway were smaller. This means that the traffic volume on the right roadway has a negative effect on road safety. The percentage of heavy vehicles had a negative significant effect on time to collision values, which indicates that time to collision values on merging tapers with heavy vehicles were smaller. This means that the percentage of heavy vehicles has a negative effect on road safety. It was found that all factors had significant effects on driving speed which were not expected in the hypothesis. However, the effect of the relative high driving speeds is debatable, since the average speed was much lower compared to the speed limit. No convergence was achieved in estimating a Linear Mixed Model for the number of lane changes, and therefore no results were obtained for this output variable.

A second linear mixed model was estimated, in which the data was divided in the defined segments. None of the factors had a significant effect on time headway. Time headway values in segment A, B and C were significantly higher compared to segment D. The highest time headway is measured in segment A, followed by segment B and C. However, this might be the result of the data adjustment described in section 4.5. The closer the participant was located to the end of the measurement area, the smaller time headway values were measured. The taper-length had a positive significant effect on time to collision values, which indicates that time to collision values on merging tapers with a long taper-length were higher. This means that the taper-length has a positive effect on road safety. No significant effect on time to collision was found for the percentage of heavy vehicles, traffic volume on the left roadway and traffic volume on the right roadway. It was found that the percentage of heavy vehicles has a negative significant effect on driving speed. However, the effect of the relative high driving speeds is debatable, since the average speed was much lower compared to the speed limit. No significant effects were found on the number of lane changes per participant.

A statistically significant interaction was found between percentage of heavy vehicles and taper-length on time to collision. The estimate indicated that the effect of taper-length on time to collision values was smaller if no heavy vehicles were present. This means that the effect of taper-length on time to collision is smaller if no heavy vehicles are present.

An overview of the results from the linear mixed model in which main effects were estimated can be found in table 5.10. The arrows indicate in which direction the factors and output variables are correlated. An arrow upwards indicates that the higher the factor, the higher the output variable. An arrow downwards indicates that the lower the factor, the lower the output variable. Highlighted arrows indicate that the effect is significant (p < 0,05).

Table 5.10: The direction of the estimates of taper-length, traffic volume and percentage of heavy vehciles on time headway (THW), time to collision (TTC), driving speed (V) and number of lane changes.

	First LLM estimation				**Second LLM estimation**			
Factor	THW	TTC	V	Lane changes	THW	TTC	V	Lane changes
Taper-length	↓	↑	**↑**	-	↓	**↑**	↑	↑
Traffic volume, left roadway	↑	↓	**↓**	-	↑	↑	↑	↓
Traffic volume, right roadway	↓	**↓**	**↓**	-	↓	↑	↑	↓
Perc. of heavy vehicles	↑	**↓**	**↓**	-	↓	↓	**↓**	↓

Results from the second questionnaire reflect the participants' opinion about the driving simulator realism. It has shown that participants were positive about the realism of the road environment such as guide rails and the road surface itself. However, participants were less positive about the realism of the events occurring during the experiment such as driving manoeuvres of other vehicles. Is is found that the participants did not experience the vehicle's characteristics as realistic. It is often stated that the experimental vehicle did not respond as expected, and the vehicle did not behave in a realistic way. Almost all participant stated that they make driving errors which they do not make in real life. The questionnaire's results indicate that the driving behaviour measured in the driving simulator may not reflect real-life driving behaviour, which must be taken into account in drawing conclusions.

6

CONCLUSIONS

6.1. DISCUSSION

A minimum of 35 merging tapers exist on Dutch motorways, and in the analysis of these locations it was found that a large share was not designed according to the design guidelines from the ROA [21]. However, these design guidelines are not scientifically underpinned. Therefore it is unclear whether the design guidelines are correct, and it is unclear whether deviating from the design guidelines has an effect on road safety. Just one old study was found in literature which contributes to the road safety on merging tapers. From these findings it can be stated that the road safety on merging tapers is unclear. This is remarkable, since road safety is one of the most important topics during the design process. However, without having scientific underpinned information it is impossible for decision makers to have a clear view on the road safety on merging tapers.

It was found that the average number of registered accidents on merging tapers was lower compared to the standard geometric design. This indicates that the "objective" road safety on merging tapers is high compared to the standard geometric design. However, in the questionnaire prior to the driving simulator experiment it was found that the subjective road safety of merging tapers is low compared to the standard geometric design. These results contradict, which can be caused by various reasons. Not many representative mergers with the standard geometric design were found, which might have caused an error in the accident data. It is also possible that driving behaviour of road users was affected by their perceived road safety; road users which perceive merging tapers as unsafe, might have adjusted their driving behaviour in such a way that it became more safe, which might have resulted in a relative low number of accidents on merging tapers.

A trend was found in the accident analysis between the traffic volume and the number of accidents and thus road safety, since most accidents occurred during peak hour. No trend was found between taper-length and the number of accidents. A trend between the percentage of heavy vehicles and the number of accidents was not studied due to lack of data. The quality of the accident data was rather poor since multiple accidents were not registered or were registered inaccurately and incomplete. However, assuming that non-registered accidents were equally divided over time and over the analysed merging taper locations, the data is still considered as useful find trends. However the number of accidents on a certain location may be influenced by other factors than the studied factor. For example, when studying a trend between taper-length and the number of accidents, the data may be influenced by the traffic volume on the studied locations. In practice it therefore turns out that finding trends in data based on the number of accidents is rather difficult. However, the trend which was found for the traffic volume on the right roadway was clear; the traffic volume on the right roadway has a negative effect on "objective" road safety, which is stated between brackets due to the poor data quality.

The second questionnaire gave information about the realism of the driving simulator. Many participants stated their driving behaviour is different from their real life driving behaviour. Errors were made which would not be made in real life, and actions performed in the driving simulator would not be performed in real life. These results indicate that the driving behaviour and thus road safety measured in the driving simulator is different from real life. However, the realism of the driving simulator was equal on each of the scenarios in the experiment. Therefore, the data obtained in the driving simulator was still useful for comparing road safety on merging tapers with road safety on mergers with the standard geometric design. Furthermore, the driving simulator was useful to analyse the effect of the different factors on driving behaviour and thus road safety.

The output variables measured during the driving simulator experiment on merging tapers and the standard geometric design were compared, but none of the mean differences were significant. However, when looking at the estimates from the LLM, it can be seen that the data seem to indicate a trend in which a merging taper is safe compared to the standard geometric design. Although the estimates were not significant, the direction in which the estimates point were not expected and remarkable, since the participants perceived merging tapers as unsafe compared to the standard geometric design. The unexpected results might be explained by the fact that only a small amount of valid datasets were available for the standard geometric design, which possibly increased the error in the results.

In the driving simulator experiment it was found that several factors had a significant effect on driving speed, although most of the effects were not expected in the hypothesis. However, during the driving simulator experiment it was observed that participants had the feeling that heavy vehicles blocked the road, so that overtaking seem to become difficult. In addition, in the second questionnaire it was found that the controllability of the driving simulator was low. These factors might have restrained participants from overtaking heavy vehicles, and might have resulted in a low driving speed compared to real life. The driving speed which was measured in the driving simulator was rather low compared to the speed limit and design speed of the motorway. Therefore, the effect of different driving speeds on road safety in this study was considered low.

The results which were found in this study can be used as a first step in studying the road safety of merging tapers in more detail. It was found in which direction taper-length, traffic volume and the percentage of heavy vehicles influence road safety on merging tapers. Results about the road safety of merging tapers compared with the standard merger design were contradictory; road users perceive merging tapers as less safe, although driving behaviour on merging tapers in the driving simulator was safer and less accidents occurred on existing merging tapers. Although the accident data was of poor quality and the driving behaviour in the driving simulator was not as realistic as in real life, the results can be of great value since they indicate a direction in which further research can be performed.

6.2. CONCLUSION

This study investigated the road safety of merging tapers compared to the standard geometric design, and the effect of taper-length, traffic volume on the left roadway, traffic volume on the right roadway and percentage of heavy vehicles on road safety at merging tapers. Two main research questions were formulated in chapter 2, which are answered based on the findings and discussion.

The first main research questions was:

"*What is the road safety on merging tapers compared to the road safety on the standard geometric design?*".

In the first questionnaire which was performed prior to the driving simulator experiment, it was found that a large share of participants stated they will feel safer on the standard geometric design compared to a merging taper. Only a very small share stated they will feel safer on merging tapers, and another small share stated they will feel equally safe on both road designs. Based on this result it is concluded that the subjective road safety on merging tapers is low compared to the standard geometric design.

In the driving simulator experiment, no significant mean differences for time headway, time to collision, driving speed and number of lane changes were measured between merging tapers and the standard geometric design. Therefore it can not be determined whether driving behaviour on merging tapers is more or less safe compared to the standard geometric merger design. It was found that the number of registered accidents on merging tapers was low compared to the standard geometric merger design. However, the number of representative locations with the standard geometric merger design was limited, and the accident data was of poor quality. Therefore, no conclusive results were found on the "objective" road safety of merging tapers, and thus further research on this topic is required.

The second main research question was:

"*How do varying road designs and traffic conditions affect the road safety on merging tapers?*".

In the driving simulator experiment, it was found that the taper-length had a positive significant effect on time to collision values. Therefore, taper-length had a negative significant effect on accident-probability; the shorter the taper-length, the higher accident-probability. This effect was expected in the hypothesis. Based on this result, it is concluded that taper-length has an effect on road safety on merging tapers; the shorter the taper-length, the lower the road safety.

From the accident data analysis it was suspected that the traffic volume had an effect on the number of accidents; the higher the traffic volume, the higher the accident-rate and thus the lower road safety. In the driving simulator experiment it was found that the traffic volume on the right roadway and the percentage of heavy vehicles had a negative significant effect on time to collision values. Therefore, these factors had a positive significant effect on accident-probability; the higher the traffic volume and the higher the percentage of heavy vehicles, the higher accident-probability. These effects were expected in the hypothesis. Based on these results, it is concluded that the traffic volume on the right roadway and the percentage of heavy vehicles have an effect on road safety on merging tapers; the higher the traffic volume on the right roadway, the lower the road safety, and the higher the percentage of heavy vehicles, the lower road safety.

6.3. STUDY LIMITATIONS

The driving simulator experiment which was performed in this study can be regarded as an innovative method for measuring road safety. Driving simulators have their own unique characteristics and it's own innovative components. A large contribution was made to the driving simulator's suitability for road safety studies, which mainly consisted of validating other vehicle's driving behaviour and adjusting driving simulator's characteristics. Furthermore the experimental road design had been build-up and programmed to make it suitable for the driving simulator experiment. Making use of the driving simulator had several advantages, such as freedom in and controllability of traffic conditions and road design, ease of data collection and safety for participants. However, due to the fact that the used driving simulator was constantly developing, and several innovative components were implemented in a limited time span, some limitations came up during the process. These are described below, and their effect on the results is described as good as possible.

The characteristics of the driving simulator's vehicle such as steering and decelerating was different compared to a real life vehicle's characteristics. As a result, driving behaviour performed in the driving simulator does not exactly reflect real-life driving behaviour, which has become clear from the questionnaire conducted after the experiment. The greater share of the participants indicated they made driving errors which they do not make in real life, and unexpected actions took place in the driving simulator. As road safety is measured by means of the performed driving behaviour, the measured road safety is different from real-life. The controllability of the driving simulator's vehicle was low, so on the one hand it can be stated that the measured road safety in the driving simulator is lower compared to real life. On the other hand, it might be that due to the uncontrollability participants were cautious during the experiment, which resulted in more safe driving behaviour. However, it may be assumed that the driving behaviour was equally non-realistic over all scenarios, and therefore the data output was convenient to determine how the factors correlate with road safety, and to compare the road safety of merging tapers with the standard geometric design. The deceleration rate of the driving simulator's vehicle was high compared to a real life vehicle. As a result, if participants wanted to decelerate slightly, it might be that a hard braking manoeuvre was performed due to the characteristics of the braking pedal. As a result, the number of braking manoeuvres might have been higher compared to real life, and the average driving speed might have been lower compared to real life.

The graphics on the screen of the driving simulator might have influenced the results from the experiment. For participants it was only possible to see the environment in front of the vehicle, which was projected on the screen. In real life, a person's sight is much wider due to the characteristics of the human eyes and the fact that a person is able to turn its body to see sideways. The driving simulator's mirrors could be used to see backwards and partly sideways, but this was a limited sight compared to real life. Furthermore the resolution of the graphics on the screen was lower compared to real life, and is limited by the available software packages and computational power. More computing power was needed for very realistic graphics, which was not available during the study. Due to these limitations, it was relative difficult for participants to judge other vehicle's location and driving speed, which is a common limitation in driving simulator studies. As a result it was difficult for participants to anticipate on other vehicle's actions such as decelerating. This might have resulted in more severe conflicts as participants noticed other vehicles too late to react sufficiently. However, the graphics were the same on all scenarios so it can be assumed that the driving simulator was still useful for the purpose of this study.

The simulated vehicle's driving behaviour was less realistic compared to real life driving behaviour. Vehicles were simulated by VISSIM, and the driving behaviour was determined from behavioural models which is based on assumptions and therefore is not completely realistic. Several validation studies about the model parameters had been reviewed in this study, and the one regarded the most realistic was chosen to create as realistic as possible driving behaviour. Furthermore, a merging taper design is not standardized in VISSIM, and thus a creative solution was needed in which overlapping links and conflict areas were used. Driving behaviour on these locations was influenced by the conflict areas, after which face validity was used to make the driving behaviour as realistic as possible. Due to driving behavioural models and the conflicts areas, the simulated vehicles did not behave as vehicles do in real life. Simulated vehicles anticipated less on other vehicles as is done in real life, for example on merging locations. For example in real life road users often give each other space so that they are able to merge. It is difficult to say how the non-realistic driving behaviour influenced the participant's driving behaviour. However, it is assumed that the possible effect on the participant's driving behaviour was equal over all scenarios.

Participant's driving behaviour might have influenced the traffic conditions during the driving simulator experiment. In real life, vehicles overtake each other if one for example wants to maintain a higher driving speed than its predecessor. Due to the low controllability of the vehicle, participants sometimes made unnecessary lane changes which were detected by VISSIM. As a result, VISSIM detected the vehicle on a specific lane, after which the faster vehicles could not overtake the participant's vehicle. As a result, it might be that the traffic volume on specific scenarios was actually lower compared to the traffic volume planned in the experimental design. A consequence of this is that the traffic density in front of the participant's vehicle might have been lower than was planned in the experimental design. This might have resulted in less conflicts compared to real life, as no vehicles were present to conflict with. This might have influenced the effect of the traffic volume on road safety on merging tapers, although for the traffic volume on the right roadway an effect on time to collision was found.

Due to the lack of computation power of VISSIM, data on merging tapers was only collected from 110 m upstream of the point of the gore until 275 m downstream of the taper-point. At the standard geometric design, data was collected from 110 m upstream of the point of the gore until 110 m downstream from the end of the expelling marking. As a result, in some situations the preceding vehicle of the participant drove outside of the data collection area, and thus time headway and time to collision were not calculated. Consequently, in some situations the participant's predecessor was located far downstream of the participant (outside the data collection area) and thus no time headway or time to collision was measured. To overcome this issue, a participant's predecessor was assumed if no predecessor was measured in the data collection area (but was possibly present). However, this assumption was regarded as not realistic for time to collision measurements, as the predecessor's driving speed needs to be estimated as well. Due to this limitation, the actual measured values for time headway and time to collision might be different than actually was the case in the experiment. In the comparison of the segments these limitations influenced the results. The closer the participant drove to the end of the data collection area, the smaller the time headway and time to collision measurements were, since no large values were measured. However, this limitation was equal throughout the experiment and therefore the results were still useful for the purpose of this study.

Based on the collected coordinates, vehicles were allocated to the lane of which the lane axis is the nearest to the middle of the vehicle. This method would be very precise if the lanes all have the same width. In the case of merging tapers, the tapered lane became narrower towards the taper-point. Towards the end of the tapered lane, the distance from the lane's axis to the side of the lane became very small. As a result, vehicles that drove close to the side of the tapered lane, were wrongly allocated to the tapered lane. At the point of the gore the lane allocation is correct. At the taper-point vehicles that drove less than 0,88 m from the side of the tapered lane were allocated to the tapered lane. In this study, time headway and time to collision values were measured for conflicting vehicles that drove in the same lane. Due to this limitation, wrong vehicles might have been assigned to a conflict and thus a wrong value of time headway or time to collision was calculated. Another consequence of this limitation might be that the number of measured lane changes was higher than the number of lane changes which really occurred, but it can not be said what the exact difference was. It was also found that the share of vehicles at the taper-point that was assigned to the tapered lane was too high, but it can not be said what the difference was. However, this limitation was equal throughout the experiment and therefore the results were still useful for the purpose of this study.

In the driving simulator experiment, the vehicle's coordinates from VISSIM were translated in 3D vehicles by Unity. The vehicle's coordinates represented the middle of the vehicle and were collected for the analysis.

The 3D vehicles which were used in the experiment did not all have the same measurements, although the vehicle's length was needed to calculate time headway and time to collision. Vehicle's lengths varied between 4,0 m and 4,6 m, with an average of 4,3 m. The vehicle's length was not collected in the data, and therefore the average of 4,3 m was assumed as the length of each vehicle. Assuming a driving speed of 100 km/h, the maximum time headway error was 0,02 s. This error was regarded as very small, and above all the error was similar in each scenario.

The quality of accident data was poor, as accidents were not always registered and if registered, the registration was often incomplete. As a result, nature and severity of accidents were often unknown, and the number of accidents was not reliable. Besides, the accident's location has a maximum error of 200 meters which is the result of the registration method. With these limitations in mind, the exact number of accidents which actually took place on a certain location might differ from the number which was found in this study. Despite of these limitations, accident data was still convenient for the purposes of the analysis, assuming that the registration error was equally divided over the considered locations and over time.

The usage of surrogate safety measures to give an assessment on road safety has some advantages since it is a pro-active method and data is highly available, but the method also brings some limitations. Accident-frequency and accident-severity is related to surrogate safety measures, but the relation may also be affected by external factors such as traffic volume and traffic composition [43]. The power of surrogate safety measures in predicting accidents depends on the strength of the additional factors. An example is given in the study of Archer [18]. It is stated that two safety critical events with similar time to collision values may be considered to have the same severity level despite significant differences in driving speed. In this situation, the event in which the highest driving speed is measured can be regarded as less safe, although this can not be concluded from the time to collision value. Tarko [43] mentions that the main challenge regarding surrogate safety measures is converting surrogate frequencies to accident frequencies. Studies on this topic used accident data from a specific road design, but it is uncertain if the relation between surrogate frequency and accident frequency is similar for other road designs. Archer [18] states that the establishment of a relationship between surrogate safety measures and accident data is attributable to the quality of accident data.

6.4. RECOMMENDATIONS AND FURTHER RESEARCH

Results from the accident analysis and driving simulator experiment did not provide evidence for the presumption that merging tapers are unsafe compared to the standard geometric design. Therefore, the application of merging tapers instead of the standard geometric design does not have to be restricted due to a high number of accidents or unsafe driving behaviour. However, it is recommended to decision makers to be cautious with applying merging tapers instead of a standard merger design, since two thirds of the participants stated they will feel safer on the standard geometric design. It is therefore recommended to only apply merging tapers if space is really limited. If a merging taper is applied, it is recommended to pay much attention to the predicted traffic volume. With the present traffic volume it might be a safe choice to apply a merging taper, but the traffic volume may become too high in the future which makes it preferable to apply the standard geometric design. It is therefore recommended to use a realistic and reliable traffic forecast. According to the taper-length, it is recommended to apply a taper-length which is at least 140 m. From the data it can not be stated which exact taper-length is safe in combination with the traffic volume and percentage of heavy vehicles. However, driving behaviour measured on merging tapers with a taper-length of at least 140 m was considered safer compared to merging tapers with a shorter taper-length. ROA [21] states that the low number of necessary lane changes of heavy vehicles is low compared to the standard merger design, which is relative safe. However, in the driving simulator experiment it was found that heavy vehicles have a negative effect on road safety. Besides it was found that the presence of heavy vehicles enlarges the negative effect of traffic volume on road safety. Therefore, it is recommended to be cautious with applying merging tapers if heavy vehicles are present.

It is recommended to get a better insight in the exact road safety on merging tapers, and the consequence of deviating from the guidelines on road safety. It might be considered whether the road safety on the existing merging tapers is sufficient, as several deviate from the design guidelines. The presumption that merging tapers are unsafe and merging taper's design guidelines are not scientifically underpinned. In this study it was found that the subjective road safety of merging tapers is indeed low, but no conclusive results were found in the driving simulator experiment and thus it is still not clear whether the presumption is correct. Besides, some of the existing merging tapers were not designed according the design guidelines. This study showed that the taper-length, traffic volume on the right roadway and percentage of heavy vehicles could have an effect on road safety. Therefore, further research is needed to clarify the road safety of merging tapers in general, and the road safety of merging tapers compared to the standard geometric design. This may both be done with accident analysis and a driving simulator experiment.

However, to make these methods more suitable for road safety studies, some recommendations are made regarding these methods. First of all, improvement of accident registration quality is recommended, as it is of poor quality now and therefore not completely reliable. Better accident data might may be very useful in road safety studies, for example when validating driving simulators and investigating the relation between surrogate safety measures and accident data. If the quality of accident data is sufficient, results may be compared with results from the driving simulator for validation purposes. Furthermore, better accident data is suitable for road safety studies although it is a re-active method. All accidents should be registered and thus must be prioritised by the police. Above all the accident registration must be exact and complete. This could for example be accomplished by using mobile applications, internet and GPS connection. With this it is relative easy to process accident details, and with a GPS connection it is possible to register the exact location of the accident. An interactive map may be build in which an overview of all accidents on Dutch roads can be seen. With an interactive map it may be much easier to perform accident analysis on certain locations, since accident can be obtained faster and with more details.

Second, it is recommended to perform road safety studies in a more realistic driving simulator. For example graphics may be improved so that the environment is better visible and other vehicle's location and speed may be assessed better. Furthermore it is recommended to improve the driving simulator vehicle's characteristics so that it's characteristics match a real life vehicle. Participants may perform more realistic driving behaviour in simulators with realistic characteristics. This may be done by using more realistic hardware such as vehicle parts from a real car, which participants are used to. Besides, scripts which translate actions in the driving simulator vehicle to actions on the screen may be improved to increase the driving simulator's realism. It is advised to use knowledge from for example formula one, in which very realistic driving simulators are used to prepare racing drivers for the race.

It is recommended to do further research on how to analyse the driving simulator's data faster. In this study, the lane's axis all were drawn based on the AutoCAD drawings, which was a time-consuming activity and is sensitive for human mistakes. It is advised to develop a method with which the lane's location can be determined from the AutoCAD drawing, and vehicles can be allocated to these lanes. Surrogate safety measures may be calculated from this data, which saves much time and prevents human mistakes.

For future driving simulator research it is recommended to use computers with higher computation power, in order that larger simulations can be performed. Higher computation power makes it possible to create an environment with a higher level of detail, which makes the driving simulator environment more realistic. In this way, the driving simulator's environment comes closer to a real life environment and more realistic result might be obtained. A higher computation power makes it possible to measure more vehicles in the simulation. In this study, the amount of vehicles from which data could be collected was limited by the computational power. As a result, conflicts were possibly not registered which resulted in an error in the results. If the computational power is higher, data of more vehicles may be collected which lowers the error. If the computation power is higher, experiments can be performed at once instead of in two parts, which saves time and keeps participants focussed on the experiment. Altogether, a higher computation power might ensure more realistic results with a smaller error.

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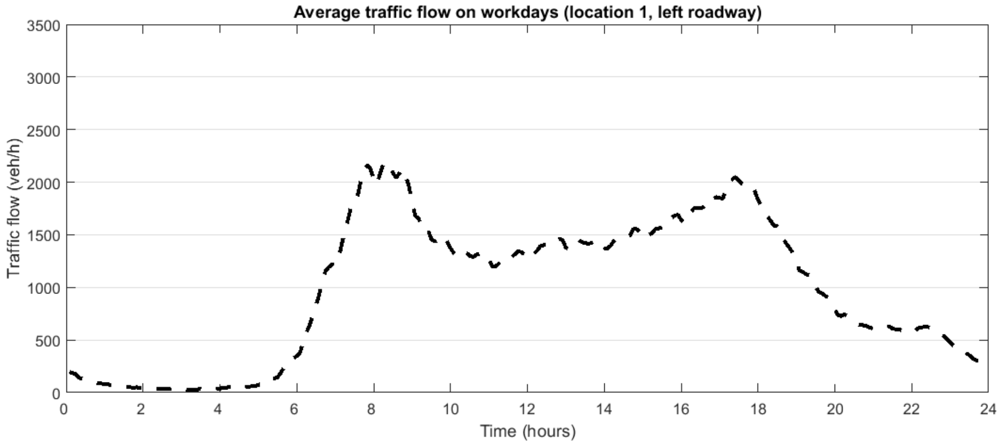
A

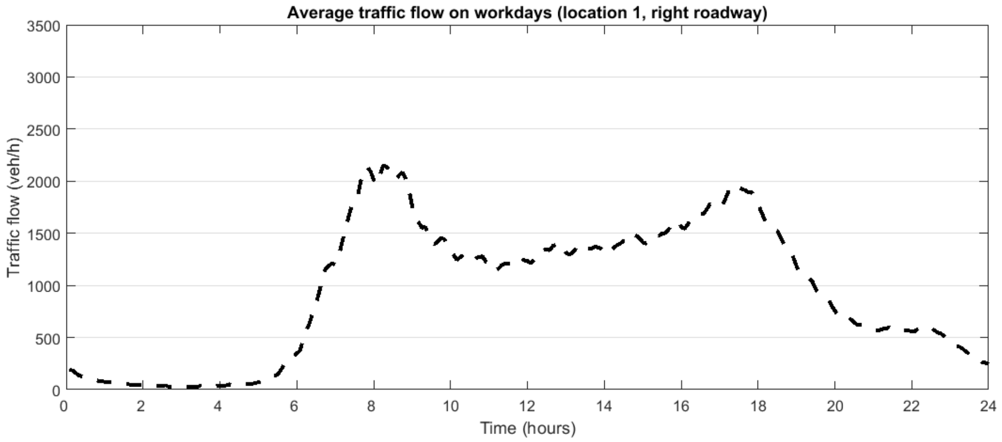
TRAFFIC FLOW DURING WEEKDAYS

This appendix gives the average traffic flow on working days on location 1 to 4 and 6 to 9. Due to the absence of suitable loop detectors on location 5, no data is available on this location.

The data is derived from loop detector data from the NDW [19] in the period 01-09-2014 to 01-09-2015.

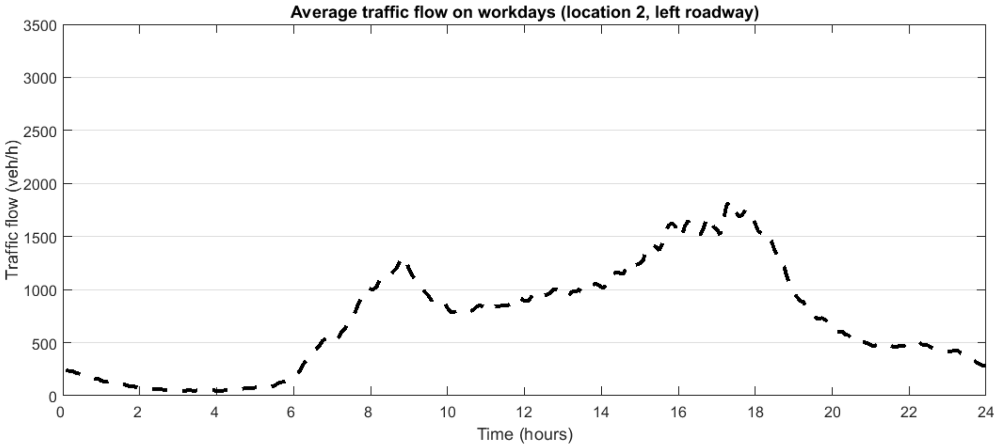


(a) Left roadway

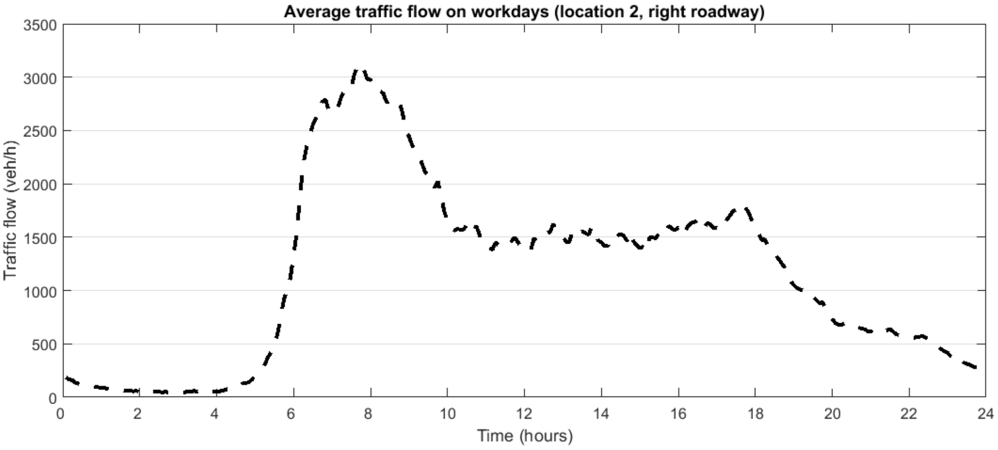


(b) Right roadway

Figure A.1: Average traffic flow during workdays on location 1

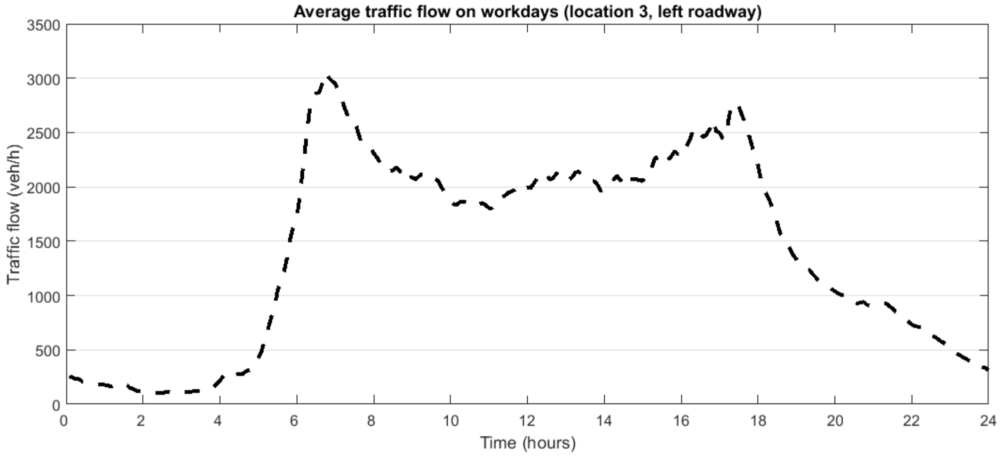


(a) Left roadway

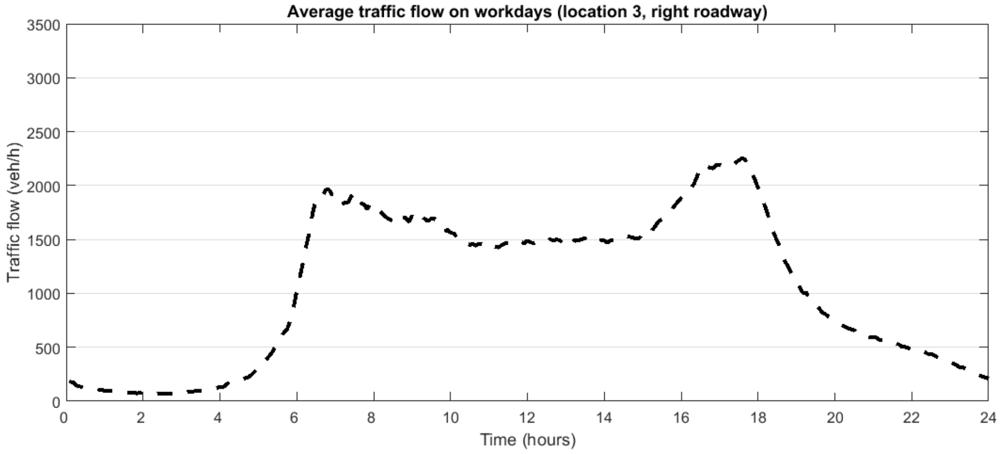


(b) Right roadway

Figure A.2: Average traffic flow during workdays on location 2

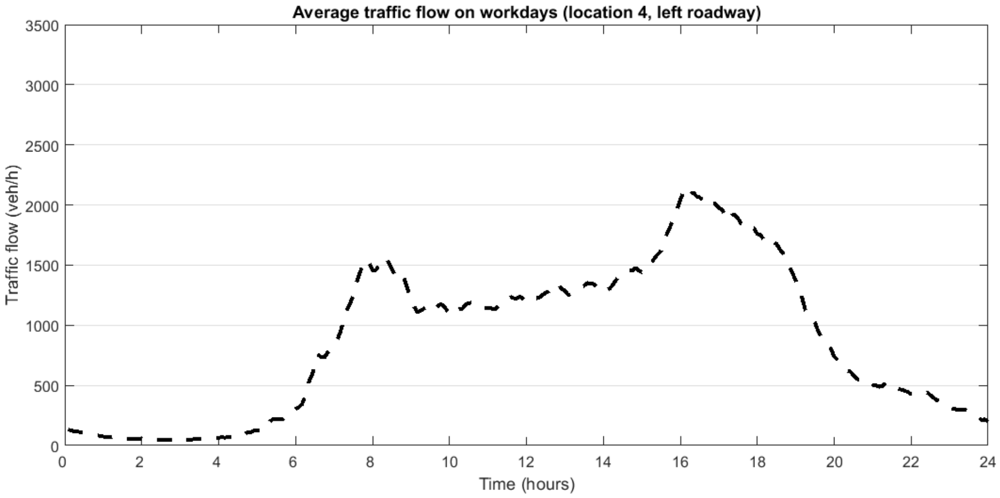


(a) Left roadway

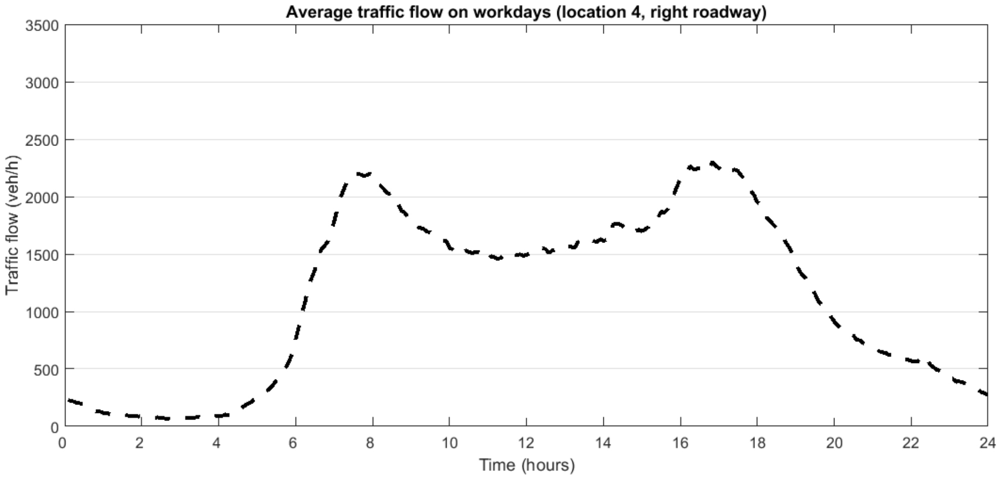


(b) Right roadway

Figure A.3: Average traffic flow during workdays on location 3

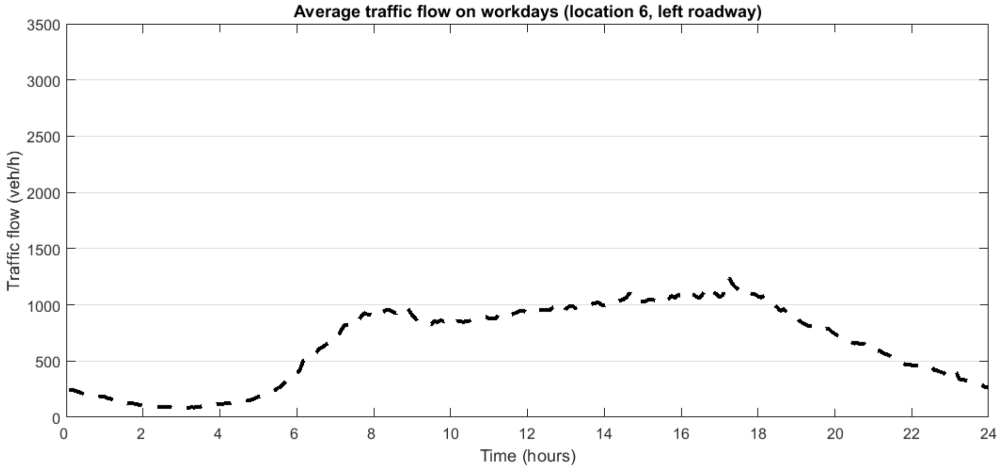


(a) Left roadway

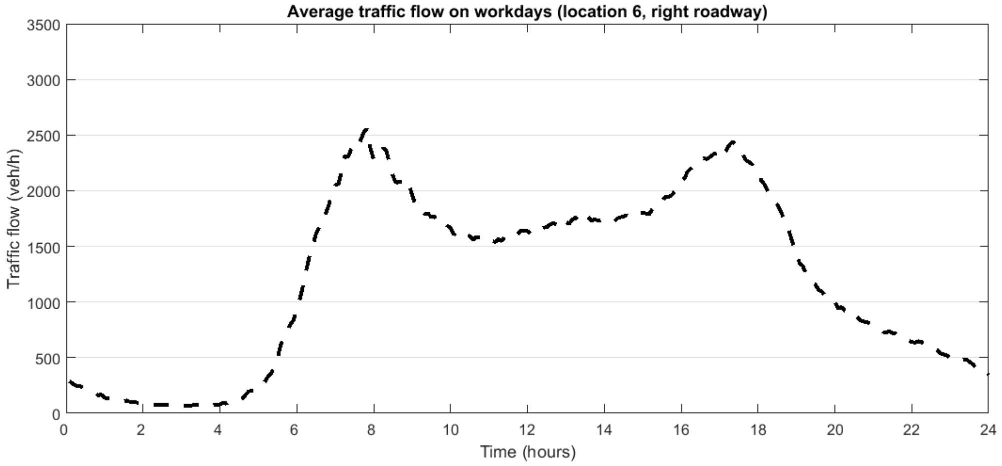


(b) Right roadway

Figure A.4: Average traffic flow during workdays on location 4

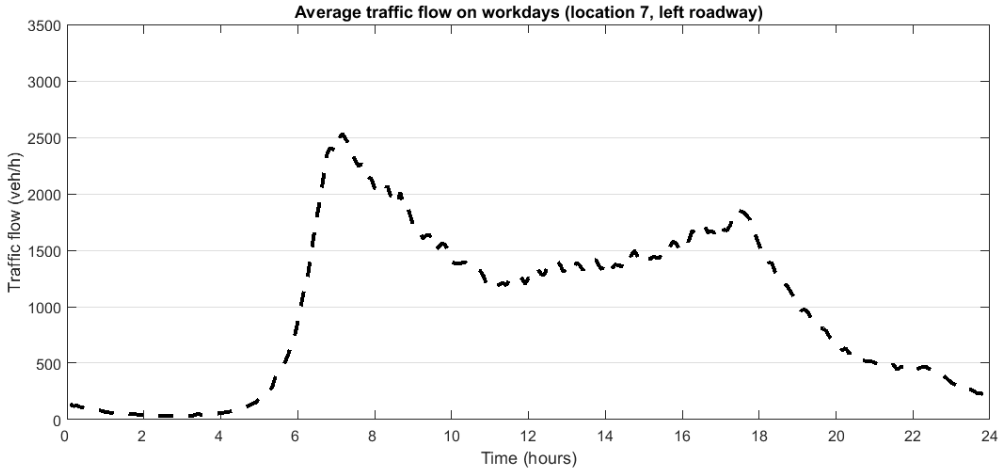


(a) Left roadway

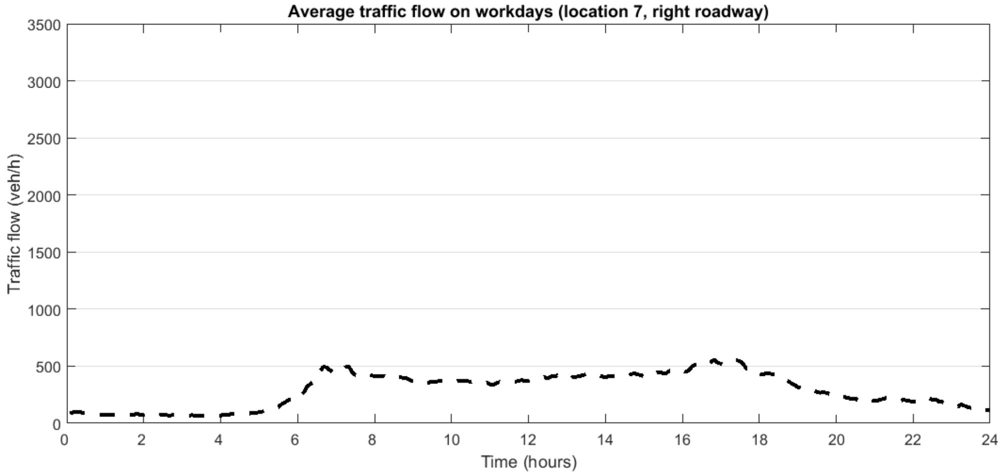


(b) Right roadway

Figure A.5: Average traffic flow during workdays on location 6

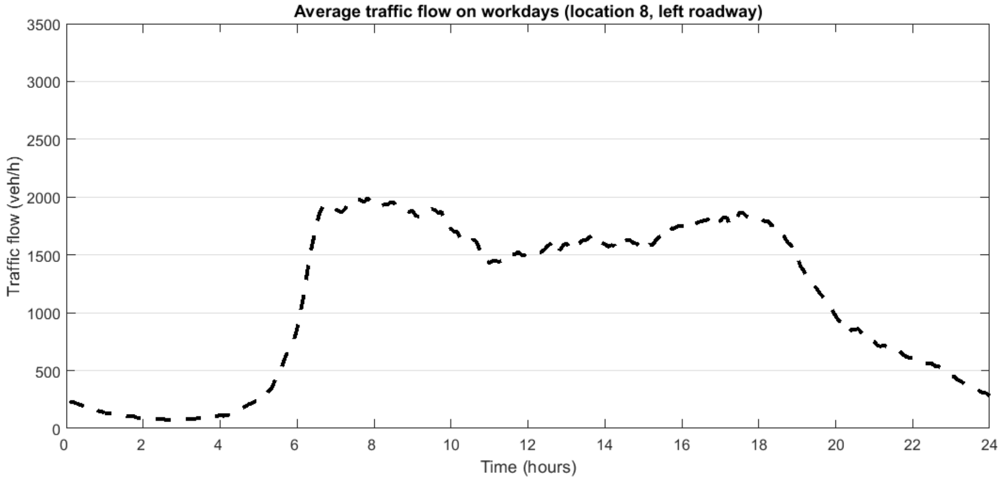


(a) Left roadway

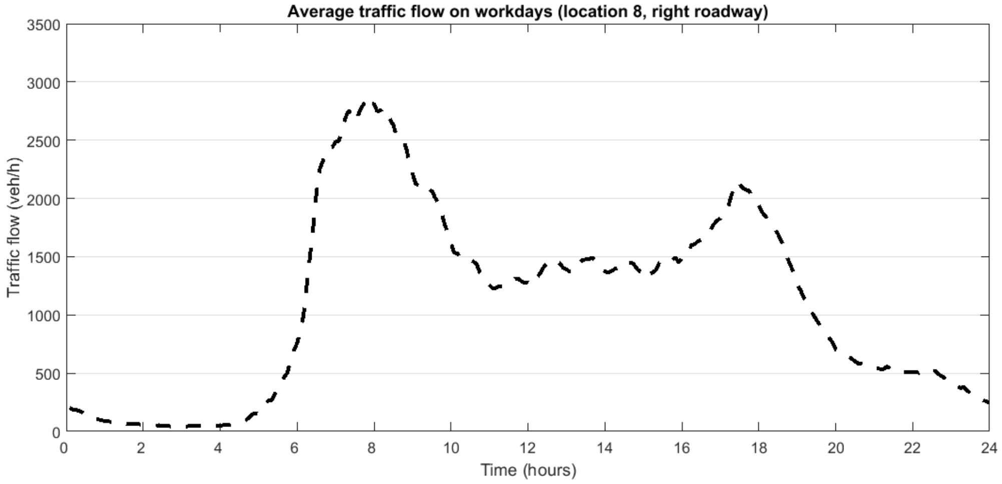


(b) Right roadway

Figure A.6: Average traffic flow during workdays on location 7

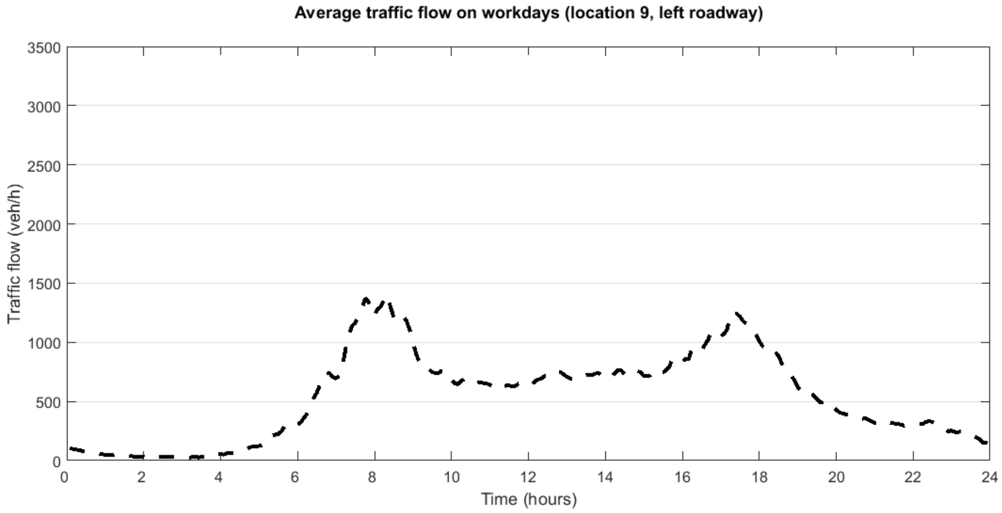


(a) Left roadway

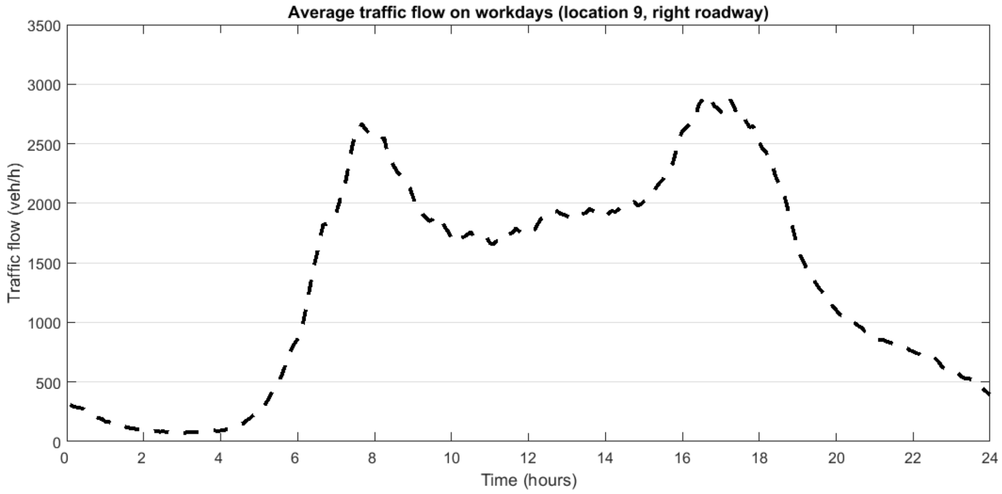


(b) Right roadway

Figure A.7: Average traffic flow during workdays on location 8



(a) Left roadway



(b) Right roadway

Figure A.8: Average traffic flow during workdays on location 9

B

GEOMETRIC DESIGN OF THE SCENARIOS

INTRODUCTION

This appendix describes the geometric design of the scenarios which are used in the driving simulator experiment. In the design process, guidelines from the NOA [4], ROA [21] and CROW [86] are used. The scenario is divided in sections, as shown in figure B.1.

A schematic overview of a part of the scenario is shown in figure B.1. The arrows indicate the driving direction. Participants start the experiment at location number 2, and must drive to the end of the scenario. Each blue rectangle indicates a section in which a merging taper is located (merging tapers are for example approached from location number 2, 5, and 8). In each section, vehicles may enter or leave the scenario. In this way, the traffic flow and the percentage of heavy vehicles in each section can be controlled.

The basis for controlling the traffic conditions (traffic flow and percentage of heavy vehicles) in each section, is that the biggest part of the vehicles which approach the merging taper on the right roadway, will leave the scenario downstream of the merging taper. Since the biggest part of the traffic volume will complete this route, these routes are called "main routes" (e.g. origin 2 to destination 4, origin 1 to destination 7, origin 5 to destination 10 (see figure B.1)). Since these vehicles approach the merging taper on the right roadway, an exit must be realized on the right side of the road (which is, above all, standard on Dutch motorways). This lowers the likelihood of congestion and dangerous situations, which influences the participants' driving behaviour.

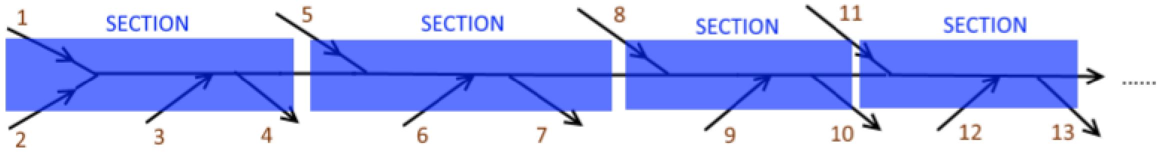


Figure B.1: A schematic representation of a part of a total scenario. In each blue rectangle, a section is designed including a merging taper.

Using VISSIM, a pilot study is performed with the section design containing the highest traffic flow. In this way, it is tested whether a certain geometric design is necessary from VISSIM's capacity point of view. From this pilot study, it can be concluded that one lane is needed for vehicles entering a scenario, and two lanes are needed for vehicles exiting a scenario. The aim is to keep the driving simulator experiment as short as possible, since simulator sickness could appear. Participants will complete the experiment in shorter time if the experimental design is relative short, therefore the aim is to limit the longitudinal distance of the geometric design. Knowing this, and the requisite of including an insertion and exit in between two sections, it is chosen to include an a-symmetric weaving area in between two sections.

B.1. GEOMETRIC DESIGN OF A SECTION

B.1.1. LONGITUDINAL DISTANCES

In order to prevent that the participants' driving behaviour on merging tapers is influenced by discontinuities upstream and downstream, certain longitudinal distances are maintained in the scenarios. Besides, participants must be able to navigate during their drive, so that they will not exit the scenario. In order to meet these two requirements, guidelines from the ROA [21] and CROW [86] are used which are based on the following:

- **Turbulence length.** The turbulence distance from the ROA [21] is defined as follows: "The turbulence distance is the distance upstream and downstream of convergence- and divergence points in which the driving behaviour and traffic flow is influenced as a result of these convergence- and divergence points." So, convergence- and divergence points cause turbulence, which is described in the NOA [4] as follows: "Turbulence is characterized by deviations in the headways between vehicles and the distribution of the traffic flow over the lanes. Related driving behaviours are e.g. braking actions, avoidance maneuvers or (anticipating) lane changes". Therefore, the turbulence length is used as a guideline for the longitudinal distance in the experiment.

  The turbulence length is found in the ROA [21], and is determined based on the design speed. The maximum speed during the experiment is 100 km/h, and therefore it is sufficient to use the turbulence distances for a design speed of 90 km/h. The principle of turbulence lengths is that the turbulence lengths of two subsequent discontinuities may not overlap each other. For example, the downstream turbulence length of discontinuity A may not overlap the turbulence length upstream of discontinuity B. If the correspondent discontinuities are both convergence points, the turbulence length of both discontinuities must be summed. In all other cases (e.g. convergence point downstream of a divergence point), half of the sum of the turbulence lengths must be taken into account.

- **Road sign distances.** Road sign distances are defined by the NOA [4] as follows: "Road sign distances are the distance between two road signs and the distance between a road sign and the divergence point, which are needed for the road user to indicate which lane or roadway must be chosen and to perform the needed actions". Road signs are the complete collection of visual messages alongside the motorway to help road users determine their route. The goal of road signs is to guide the road user to his/her destination. By applying road signs at a certain distance upstream of a divergence point, road users are able to chose the correct lane. The road sign distance guidelines are given in the "Richtlijn bewegwijzering 2014" [86].

The applied longitudinal distance depends on whether the turbulence distance or road sign distance is leading. Besides, upstream of the merging taper the longitudinal distance is enlarged because the decisive distance is perceived too short. The applied lane drop could influence the participants' driving behaviour at the merging taper, and therefore the longitudinal distance is enlarged. An overview of the used distances and the location of each road sign is shown in figure B.2. Distances are given in meters. Distances between road signs are given in red, and an explanation of each road sign is given in table B.1.

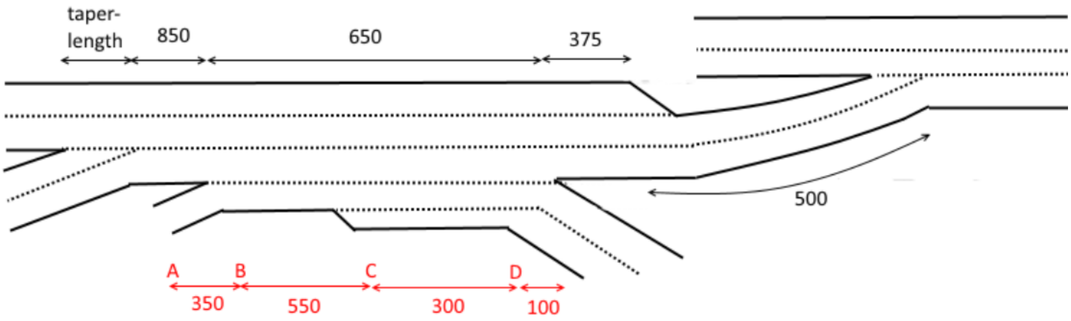


Figure B.2: Schematic representation of a section, including longitudinal distances.

Table B.1: Explanation of the road sign locations given in figure B.2. Explanations derived from the CROW [86].

Location	Explanation
A	*Announcement road sign*: Indicates the weaving area downstream on large distance of the divergence point
B	*In advance road sign*: Gives information about the destinations in both directions
C	*In advance road sign*: Gives information about the destinations in both directions
D	*Decision road sign*: Information about the actions which must be taken

B.1.2. CROSS-PROFILE VIEW OF THE ROAD IN GENERAL

The cross-profile of the road is designed according to the geometric design guidelines from the ROA [21]. These guidelines are commonly used on Dutch motorways. A standard lane width of 3,50 meters is applied. The width includes half of the dividing line width, and excludes the width of the side line and possible blocked line. The width of the emergency lane is 3,70 excluding the width of the side line. The redress lane is 1,00 meter including half of the side line width. An overview of the distances in the cross-section is shown in figure B.3.

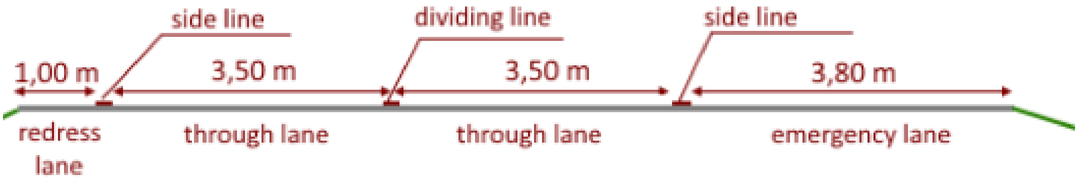


Figure B.3: Cross-section of the roadway designed in the experiment

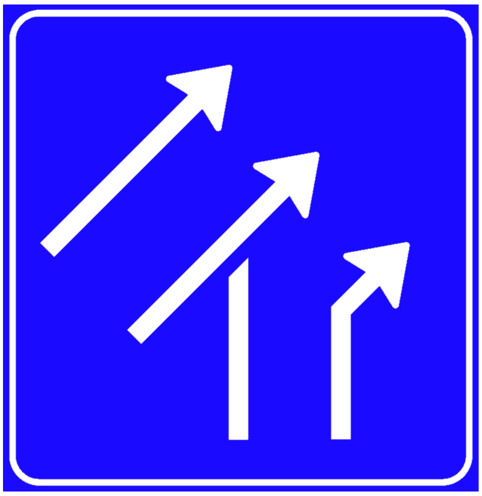
B.1.3. MERGING TAPER

The merging taper is designed according to the geometric design guidelines from the ROA [21]. It states that the roadways 100 meter upstream of the convergence point must be straight or nearly straight (R>4000 m). The angle between the converging roadways must not be bigger than 3%, which is equal to 1,72°. An overview of the most important aspects of the geometric design is shown in figure B.4, and are stated below:

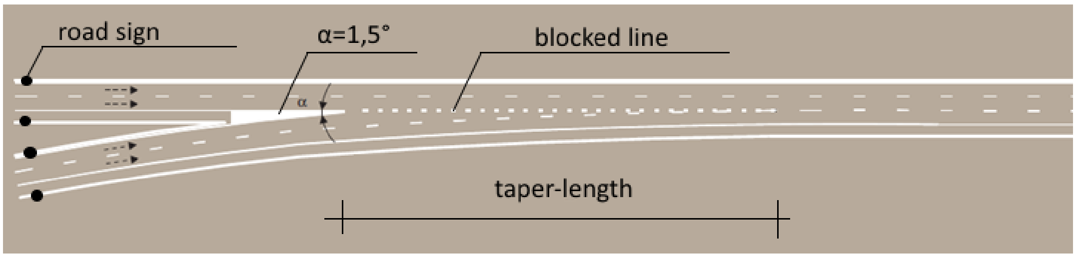
- The angle between the two roadways is 1,5°;
- Starting from 100 meter upstream of the merging taper, both roadways are straight;
- Alongside the tapered road section, a blocked line is applied between the left roadway and right roadway, in order to indicate where the tapered lane is situated;
- On both roadways, 150 metres upstream of the convergence point a road sign is placed on both sides of the road. On this road sign, the merging taper is announced [87].

B.2. GEOMETRIC DESIGN IN BETWEEN SECTIONS

Downstream of the weaving area, a lane drop is applied on the 3-lane roadway. This results in a 2-lane roadway on which the participant drives to the next section. The participants' driving behaviour in the upfollowing section must not be influenced by the traffic conditions and geometric design on the weaving area. When taking into account turbulence length, the distance between the point of the gore of the divergence and the point of the gore of the convergence point must be at least 220 meters [4]. Assuming an average speed of 100 km/h, this distance is completed in 8 seconds. By estimation, this distance is insufficient, since the participants' driving behaviour must not be influenced by the divergence point upstream. The participants' capabilities to control the driving simulator is a factor which influences this length (assuming that participants control the driving simulator less good than a real-life vehicle, the length must be longer). From expert judgment, a sufficient distance between the point of the gore of the divergence point and the point of the gore of the convergence point is 800 meters. Assuming an average speed of 100 km/h, this distance can be completed in around 30 seconds. In this time, it is assumed that the participants' driving behaviour is not influenced by the divergence point.



(a) Road sign on which the merging taper is announced. On each dot in figure B.4 b, one of such road signs is placed.



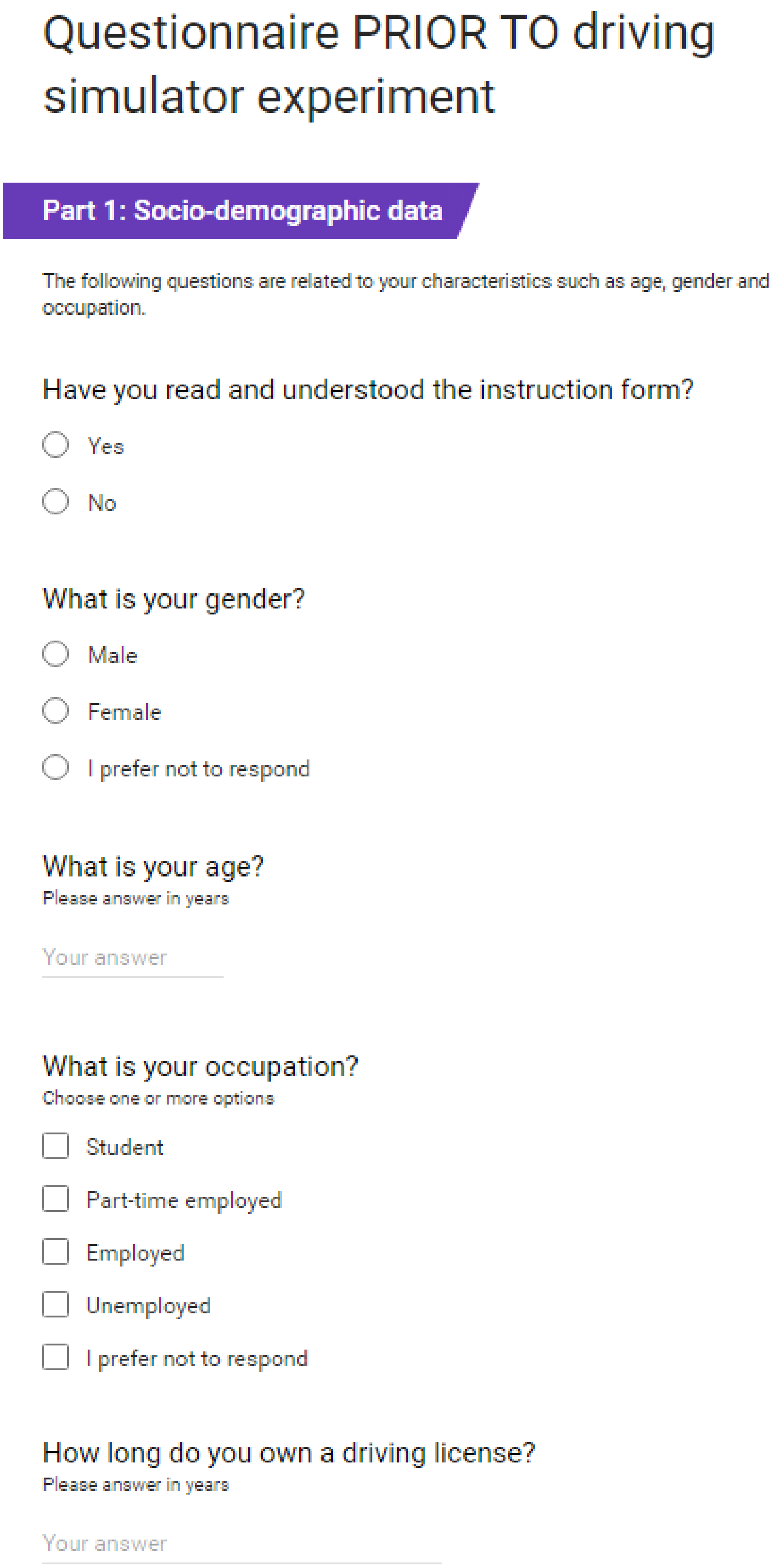
(b) Schematic overview of the most important aspects of the geometric design of the experiment's merging tapers

Figure B.4: Geometric design of the experiment's merging tapers, and road sign which announces the merging taper.

C

QUESTIONNAIRE PRIOR TO THE DRIVING SIMULATOR EXPERIMENT

In this appendix, the questions given in the questionnaire prior to the driving simulator experiment, are given.



Questionnaire PRIOR TO driving simulator experiment

Part 1: Socio-demographic data

The following questions are related to your characteristics such as age, gender and occupation.

Have you read and understood the instruction form?

○ Yes

○ No

What is your gender?

○ Male

○ Female

○ I prefer not to respond

What is your age?
Please answer in years

Your answer

What is your occupation?
Choose one or more options

☐ Student

☐ Part-time employed

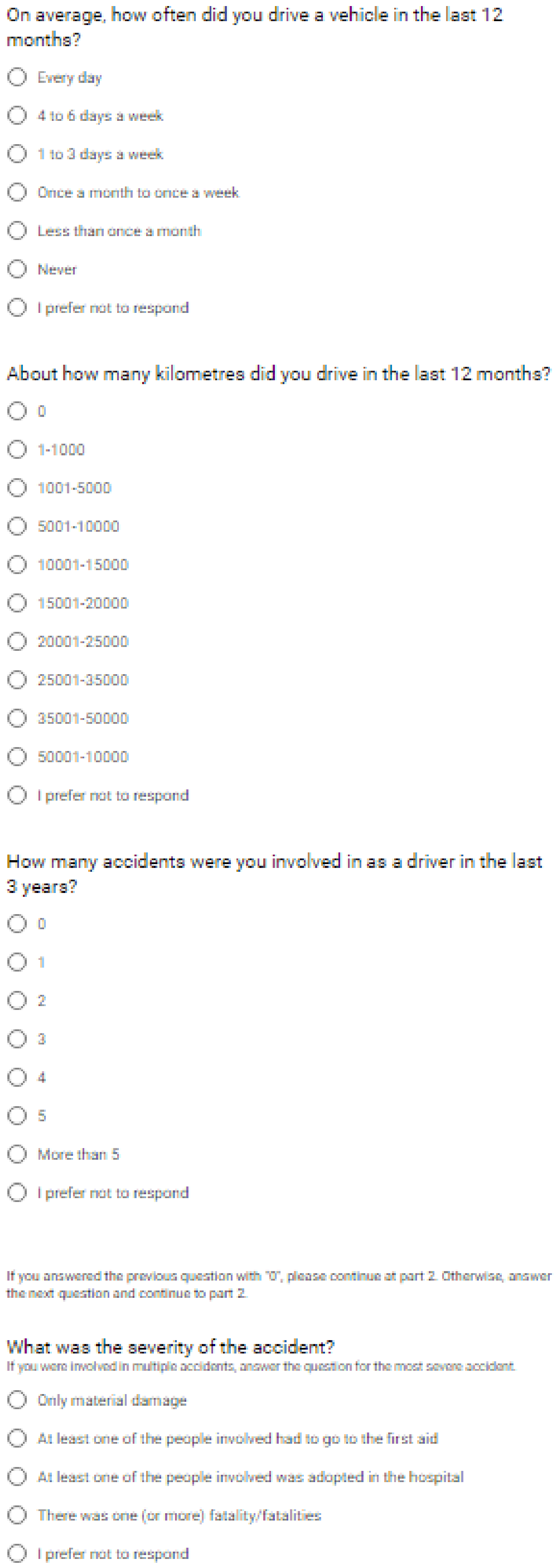
☐ Employed

☐ Unemployed

☐ I prefer not to respond

How long do you own a driving license?
Please answer in years

Your answer



On average, how often did you drive a vehicle in the last 12 months?

○ Every day

○ 4 to 6 days a week

○ 1 to 3 days a week

○ Once a month to once a week

○ Less than once a month

○ Never

○ I prefer not to respond

About how many kilometres did you drive in the last 12 months?

○ 0

○ 1-1000

○ 1001-5000

○ 5001-10000

○ 10001-15000

○ 15001-20000

○ 20001-25000

○ 25001-35000

○ 35001-50000

○ 50001-10000

○ I prefer not to respond

How many accidents were you involved in as a driver in the last 3 years?

○ 0

○ 1

○ 2

○ 3

○ 4

○ 5

○ More than 5

○ I prefer not to respond

If you answered the previous question with "0", please continue at part 2. Otherwise, answer the next question and continue to part 2.

What was the severity of the accident?

If you were involved in multiple accidents, answer the question for the most severe accident.

○ Only material damage

○ At least one of the people involved had to go to the first aid

○ At least one of the people involved was adopted in the hospital

○ There was one (or more) fatality/fatalities

○ I prefer not to respond

Part 2: Geometric design of roadways

The following questions are related to your knowledge and perception of roadways' geometric design.

Please read carefully the following paragraph before answering the remaining of the questionnaire.

On Dutch motorways, two roadways can merge to one roadway (merger/samenvoeging), which is shown in figure 1. Sometimes, from a capacity point of view, one lane less is needed after the merger. There are two options to design such merger. One option is shown in figure 2, in which a lane drop is applied on the left lane. The other option is shown in figure 3, in which a merging taper (taper-samenvoeging) is applied.

Figure 1: Merger/Samenvoeging

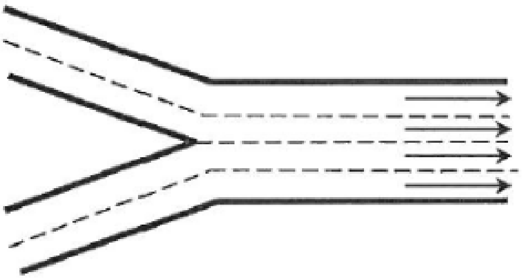


Figure 2: Option number one: Apply a lane drop on the left lane

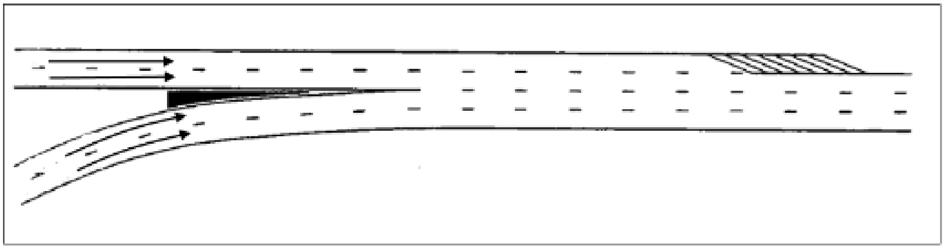
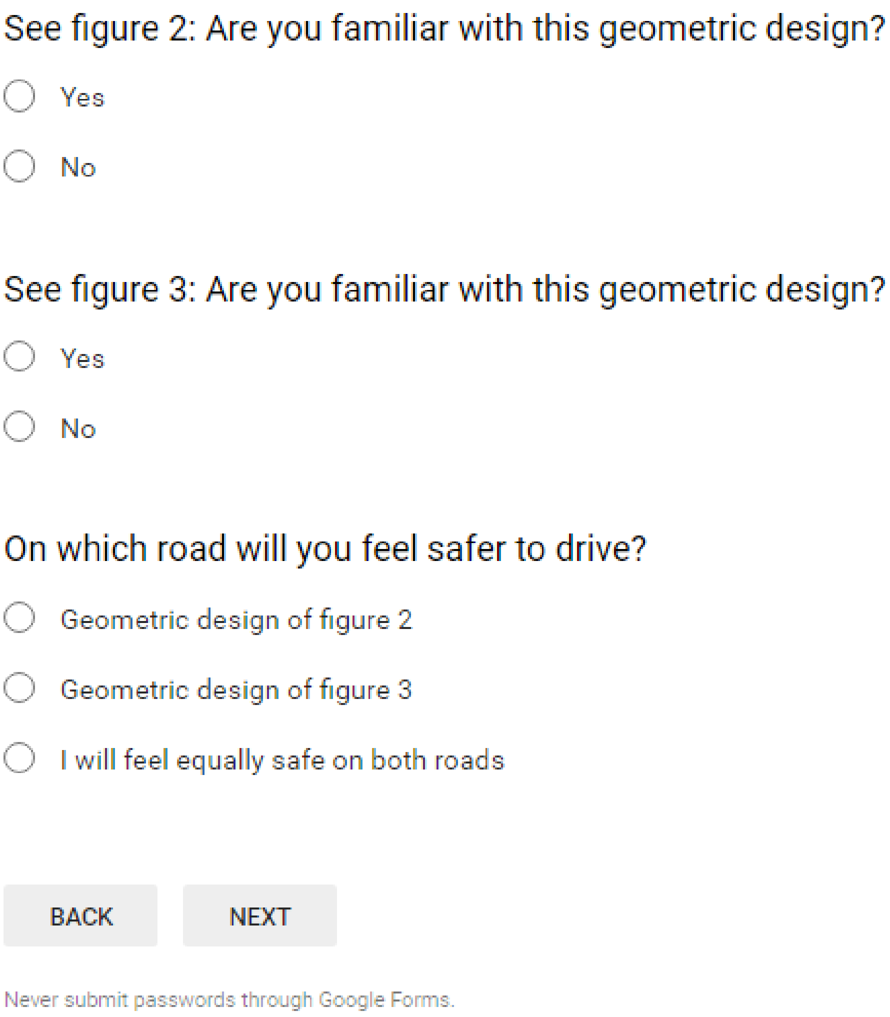


Figure 3: Option number two: Apply a merging taper



See figure 2: Are you familiar with this geometric design?

○ Yes

○ No

See figure 3: Are you familiar with this geometric design?

○ Yes

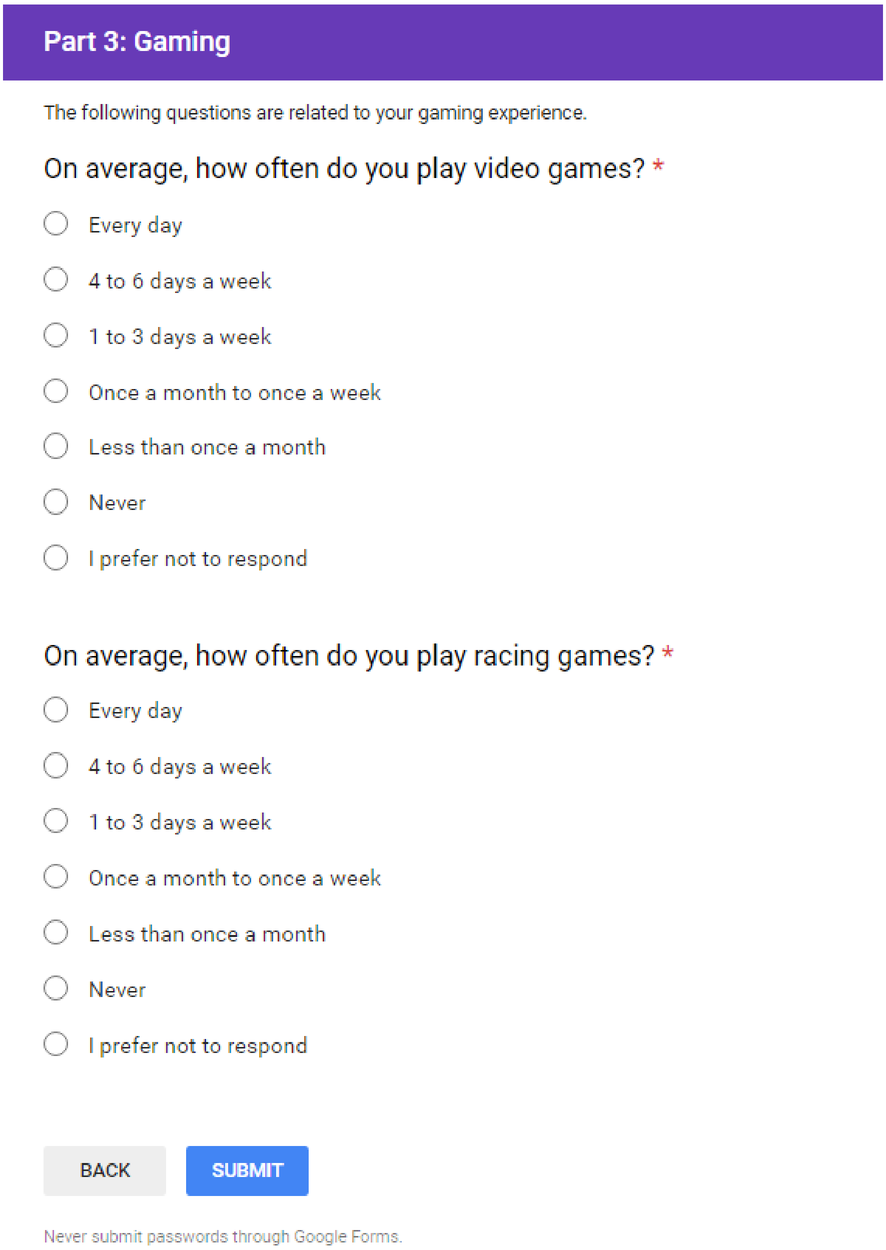
○ No

On which road will you feel safer to drive?

○ Geometric design of figure 2

○ Geometric design of figure 3

○ I will feel equally safe on both roads



Part 3: Gaming

The following questions are related to your gaming experience.

On average, how often do you play video games? *

○ Every day
○ 4 to 6 days a week
○ 1 to 3 days a week
○ Once a month to once a week
○ Less than once a month
○ Never
○ I prefer not to respond

On average, how often do you play racing games? *

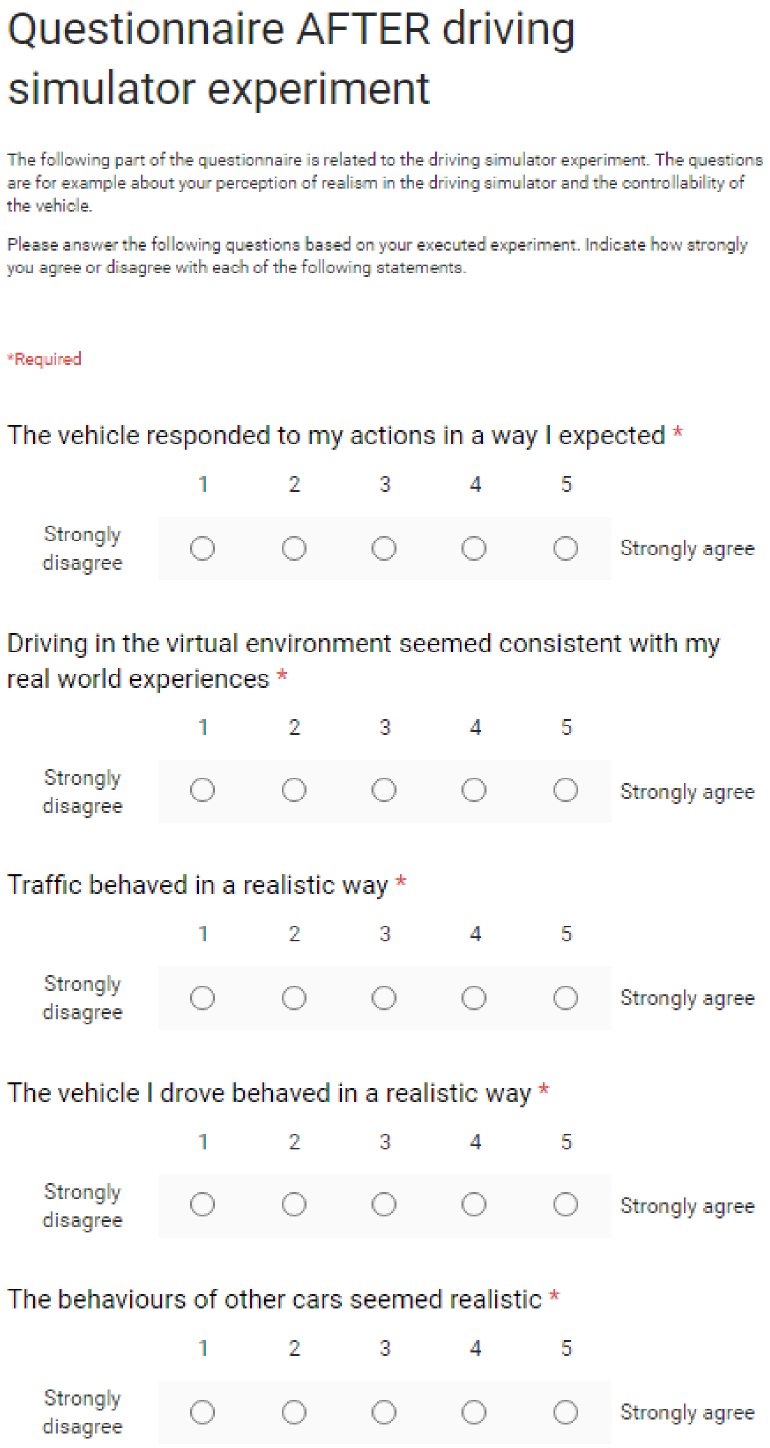
○ Every day
○ 4 to 6 days a week
○ 1 to 3 days a week
○ Once a month to once a week
○ Less than once a month
○ Never
○ I prefer not to respond

Never submit passwords through Google Forms.

D

QUESTIONNAIRE AFTER THE DRIVING SIMULATOR EXPERIMENT

In this appendix, the statements given in the questionnaire after the driving simulator experiment, are given. Answers must be given from a 5-point Likert scale, on which 1 is equal to *strongly disagree* and 5 is equal to *strongly agree*.



Questionnaire AFTER driving simulator experiment

The following part of the questionnaire is related to the driving simulator experiment. The questions are for example about your perception of realism in the driving simulator and the controllability of the vehicle.

Please answer the following questions based on your executed experiment. Indicate how strongly you agree or disagree with each of the following statements.

*Required

The vehicle responded to my actions in a way I expected *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Driving in the virtual environment seemed consistent with my real world experiences *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Traffic behaved in a realistic way *

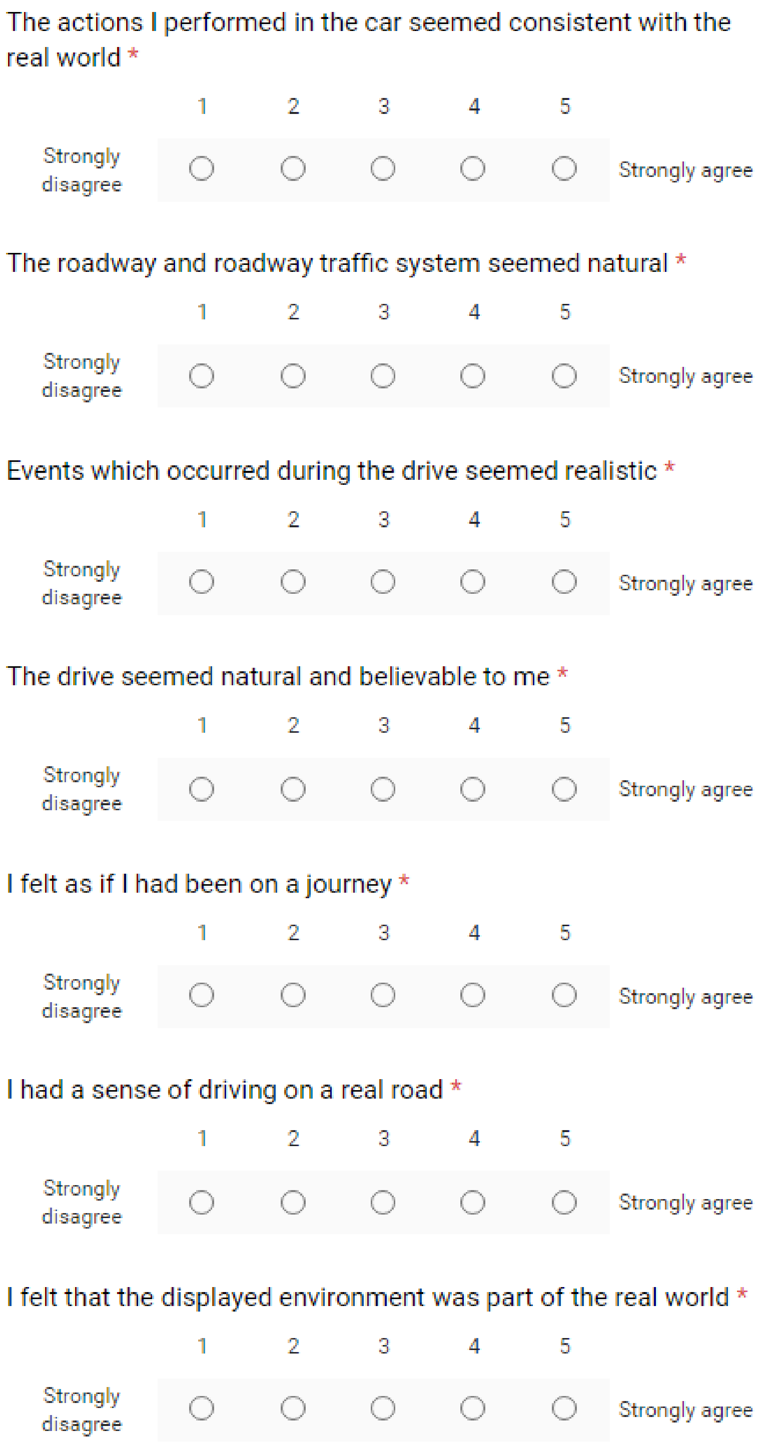
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The vehicle I drove behaved in a realistic way *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The behaviours of other cars seemed realistic *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



The actions I performed in the car seemed consistent with the real world *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The roadway and roadway traffic system seemed natural *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Events which occurred during the drive seemed realistic *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The drive seemed natural and believable to me *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt as if I had been on a journey *

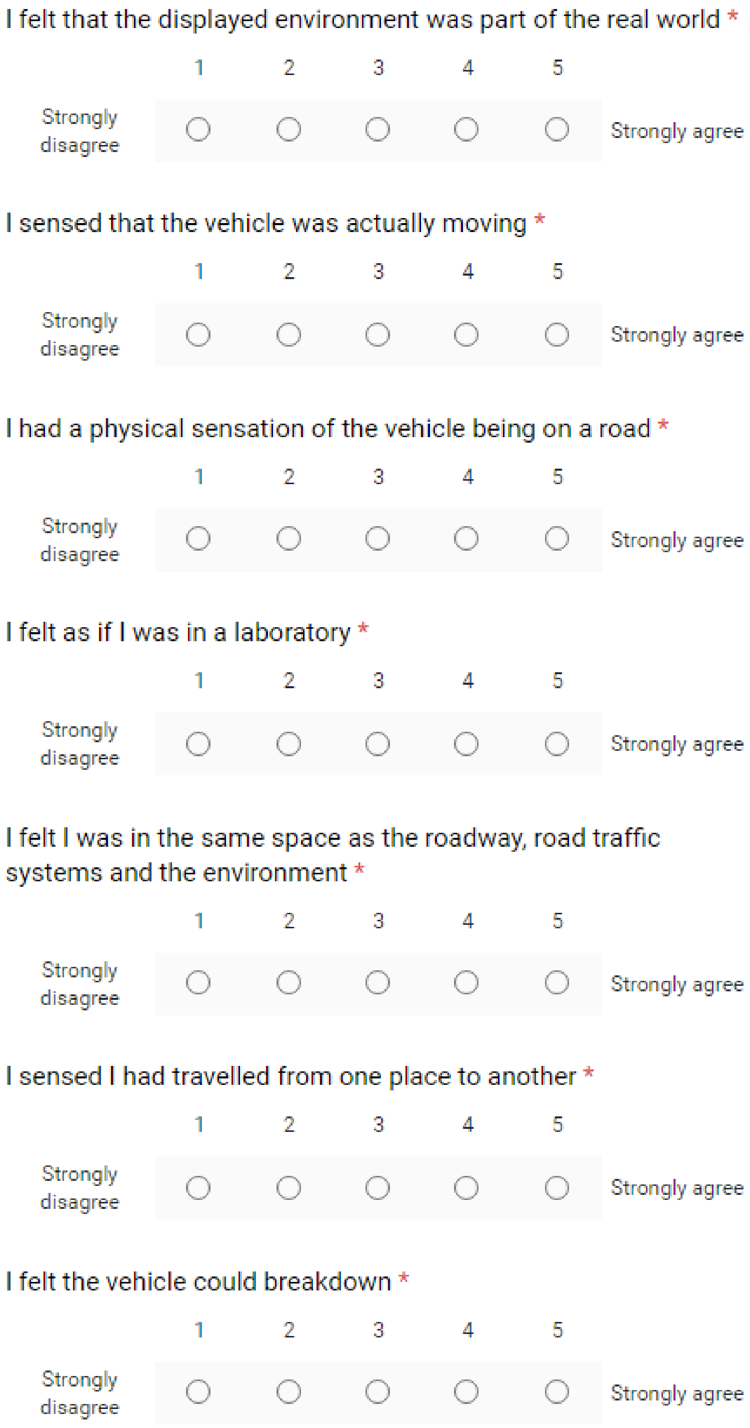
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a sense of driving on a real road *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt that the displayed environment was part of the real world *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



I felt that the displayed environment was part of the real world *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I sensed that the vehicle was actually moving *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a physical sensation of the vehicle being on a road *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt as if I was in a laboratory *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt I was in the same space as the roadway, road traffic systems and the environment *

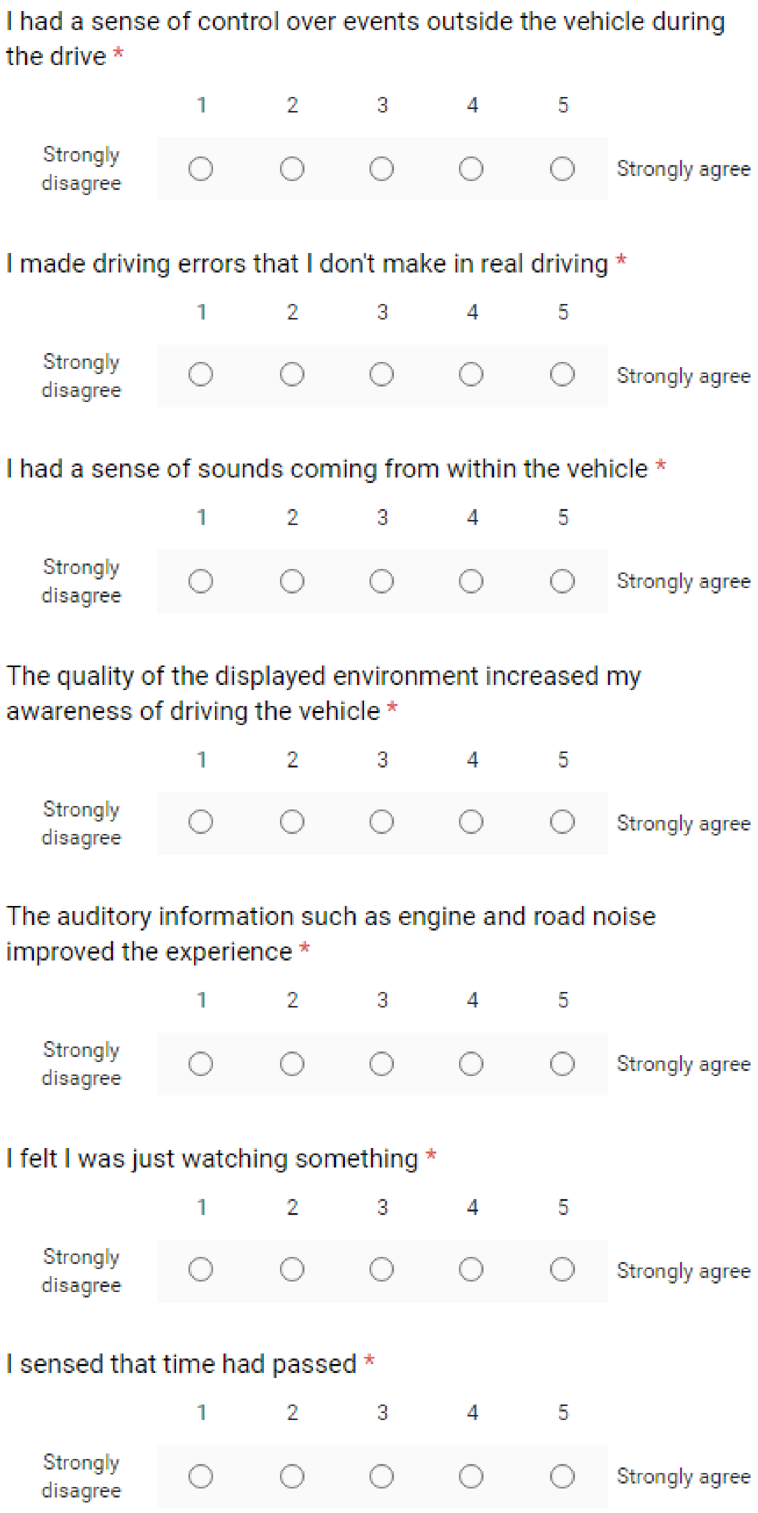
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I sensed I had travelled from one place to another *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt the vehicle could breakdown *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



I had a sense of control over events outside the vehicle during the drive *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I made driving errors that I don't make in real driving *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a sense of sounds coming from within the vehicle *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The quality of the displayed environment increased my awareness of driving the vehicle *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The auditory information such as engine and road noise improved the experience *

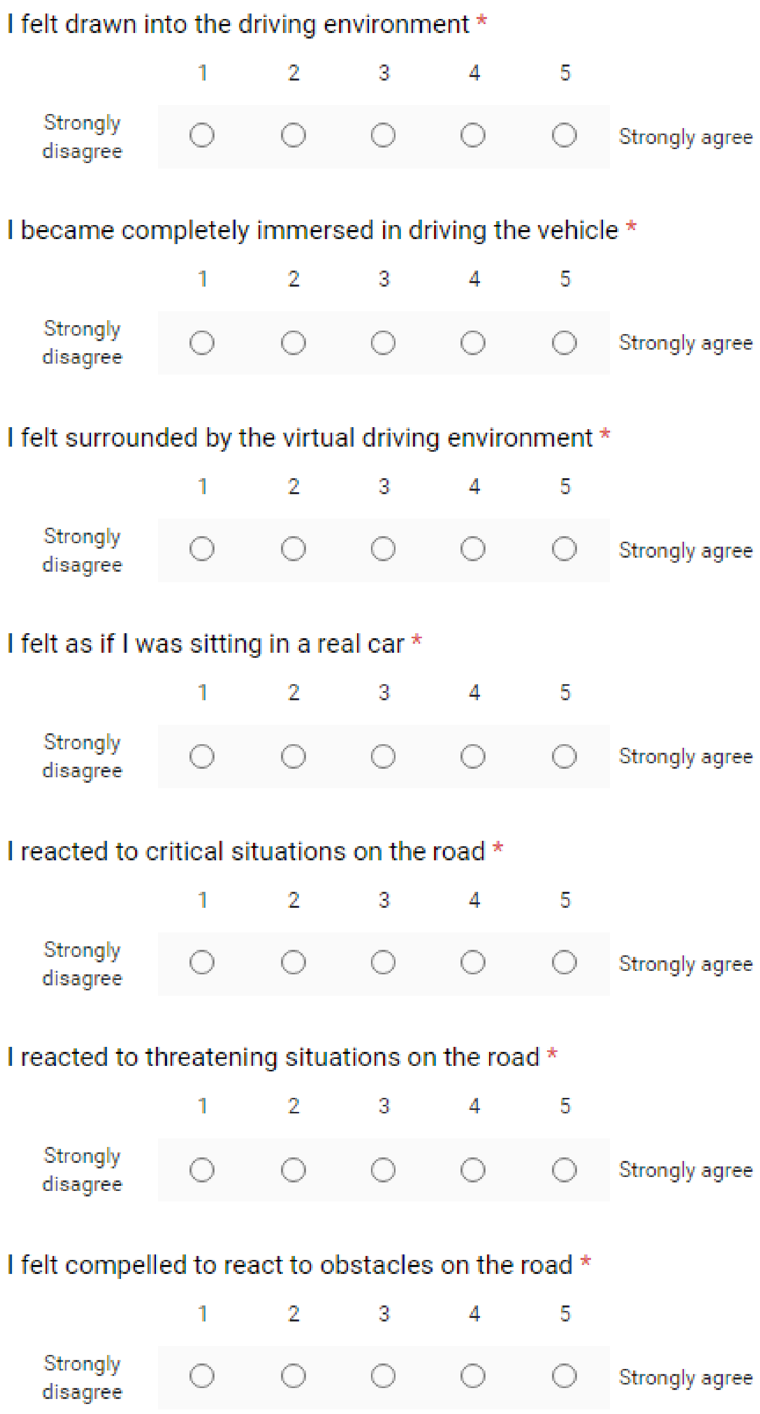
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt I was just watching something *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I sensed that time had passed *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



I felt drawn into the driving environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I became completely immersed in driving the vehicle *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt surrounded by the virtual driving environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt as if I was sitting in a real car *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I reacted to critical situations on the road *

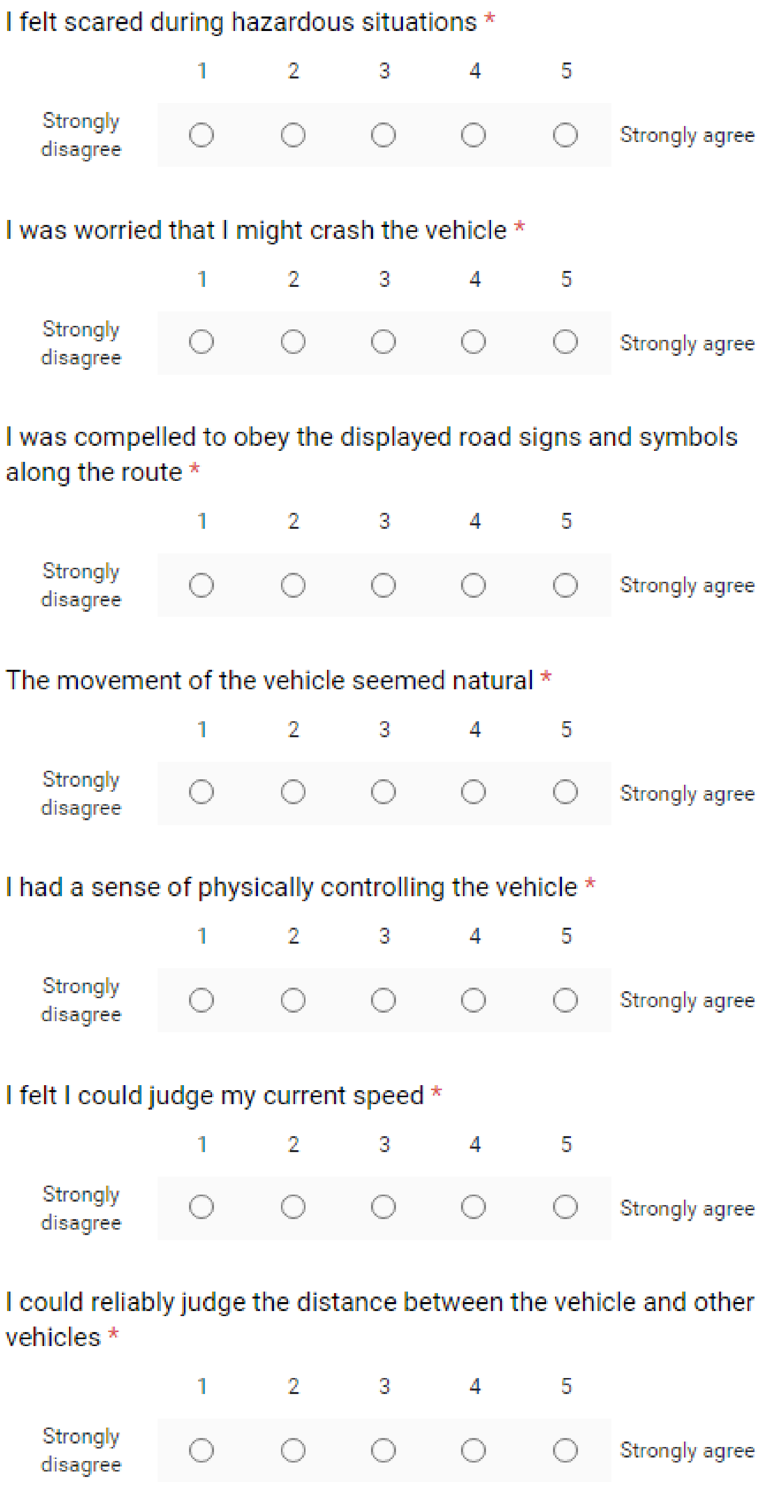
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I reacted to threatening situations on the road *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt compelled to react to obstacles on the road *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



I felt scared during hazardous situations *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I was worried that I might crash the vehicle *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I was compelled to obey the displayed road signs and symbols along the route *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The movement of the vehicle seemed natural *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a sense of physically controlling the vehicle *

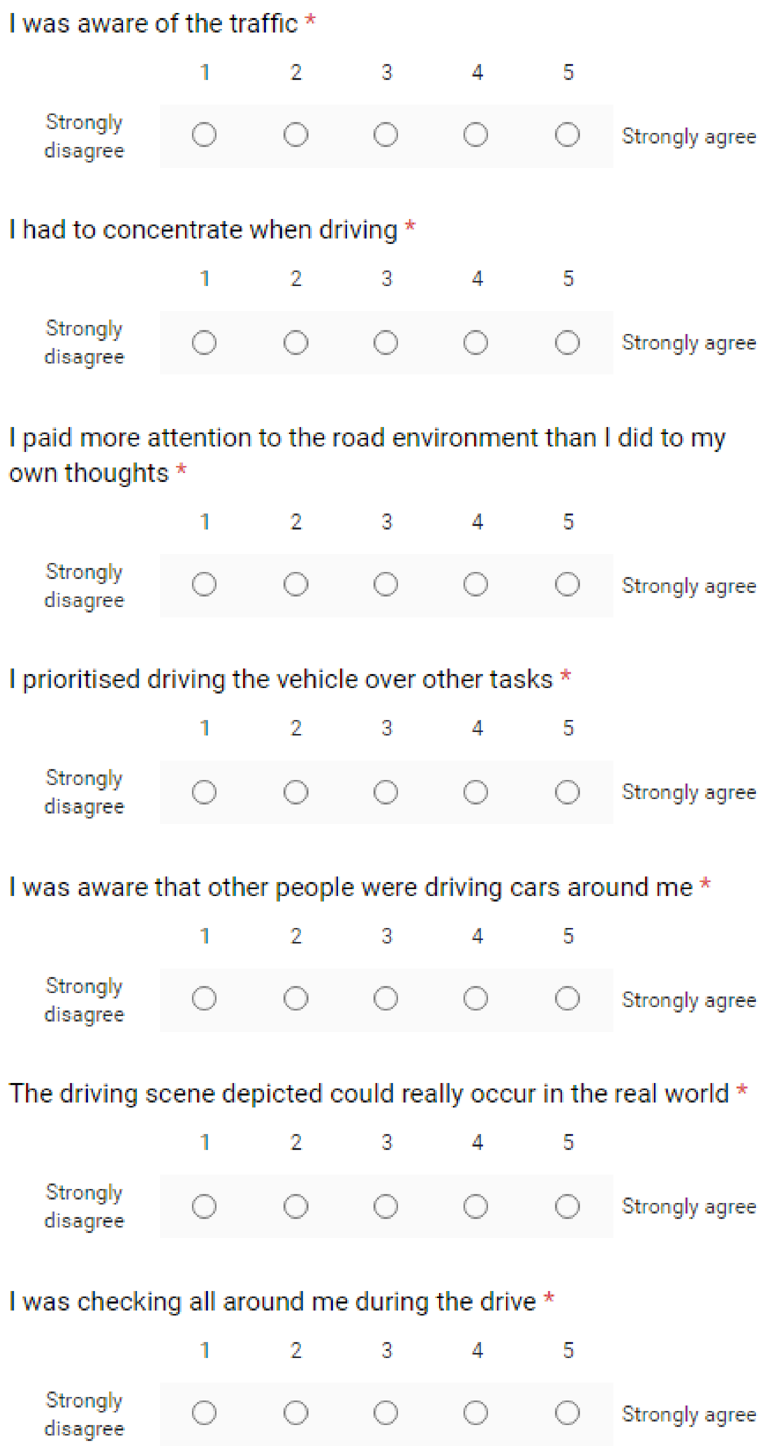
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt I could judge my current speed *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I could reliably judge the distance between the vehicle and other vehicles *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



I was aware of the traffic *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had to concentrate when driving *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I paid more attention to the road environment than I did to my own thoughts *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I prioritised driving the vehicle over other tasks *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I was aware that other people were driving cars around me *

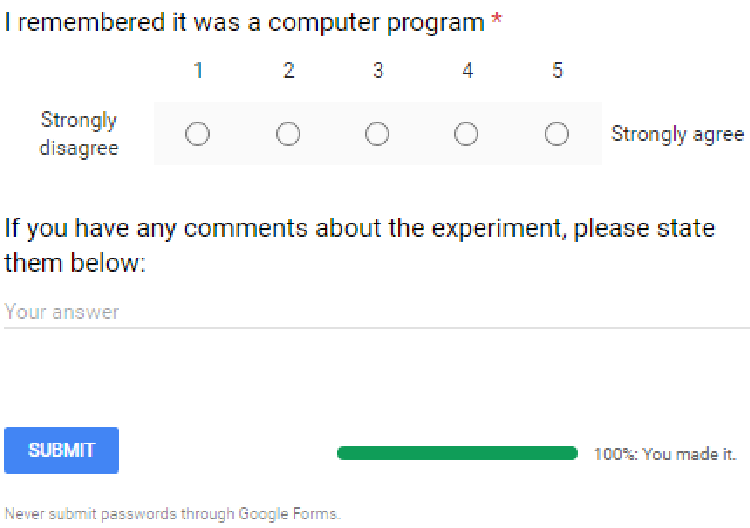
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The driving scene depicted could really occur in the real world *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I was checking all around me during the drive *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



I remembered it was a computer program *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

If you have any comments about the experiment, please state them below:

Your answer

100%: You made it.

Never submit passwords through Google Forms.

E

PARTICIPANTS' INTRODUCTION TO THE EXPERIMENT

Thank you for participating in this experiment. This study is being conducted by Matthijs de Ruyter, a MSC student at the Department of Transport and Planning, TU Delft.

This experiment takes approximately 45 minutes to complete. Please, take notice of the following points:

- The data collected in this experiment is saved anonymously, just the time stamp of completing the experiment is saved.
- If you experience any discomfort during the experiment, you have the right to abandon the experiment at any time.

E.1. INTRODUCTION TO THE EXPERIMENT

In this experiment, you are asked to drive in the driving simulator. Prior to the driving simulator experiment and after the driving simulator experiment you are asked to fill in a questionnaire.

The total experiment consists of 4 parts, and is performed in the sequence presented below. A more detailed explanation about the questionnaires and driving simulator experiment is given in the up-following sections.

- **Part 1:** Questionnaire A (5 min)
- **Part 2:** Driving simulator training (10 min)
- **Part 3:** Driving simulator experiment (15 min)
- **Part 4:** Questionnaire B (10 min)

E.1.1. QUESTIONNAIRES

Questionnaire A consists of 14 questions. Questionnaire B consists of 47 questions.

The following topics are covered in the questionnaires:

- Socio-demographic data
- Knowledge about geometric designs
- Experience with video games
- Your perception of reality in the driving simulator
- Your perception of control in the driving simulator

E.1.2. DRIVING SIMULATOR

In part 2 of the experiment you will drive on a road in order to become familiar with the driving simulator and the virtual environment. After this part, the final driving simulator experiment will take place (part 3).

The driving simulator consists of the following components:

- Drivers seat
- Steering wheel (The buttons and flippers should not be used)
- Pedals (This is an automatic car, you should only use the right and middle pedal, which are respectively throttle and brake. The left pedal should not be used)
- Virtual reality glass

INSTRUCTIONS:

1. Please adjust the seat to your comfortable position
2. Get familiar with the steering wheel, accelerator and brake pedal
3. Please use the adjustable strap in order to make the VR glass comfortable
4. After putting on the VR glass, your position in the vehicle will be calibrated
5. Please make yourself comfortable with the mirrors of the vehicle

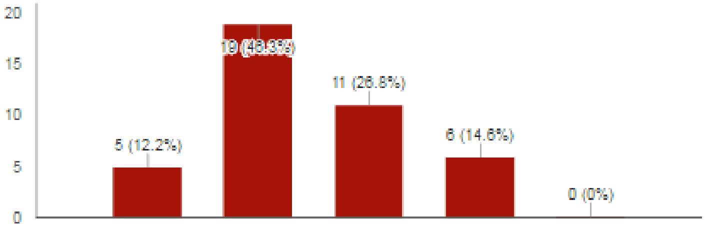
The experiment starts from this point

6. Your destination is Amsterdam, this destination can be found by following the main road
7. Please follow Dutch traffic regulations as you should do in real life (the speed limit is 100 km/h)

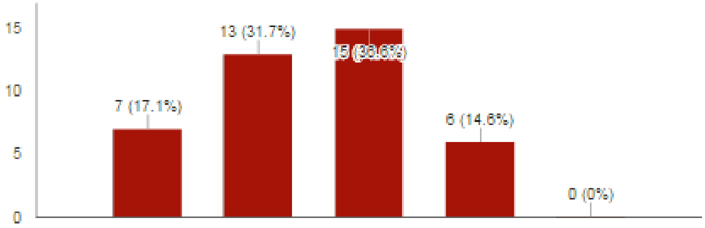
F

QUESTIONNAIRE AFTER TO THE DRIVING SIMULATOR EXPERIMENT: RESULTS

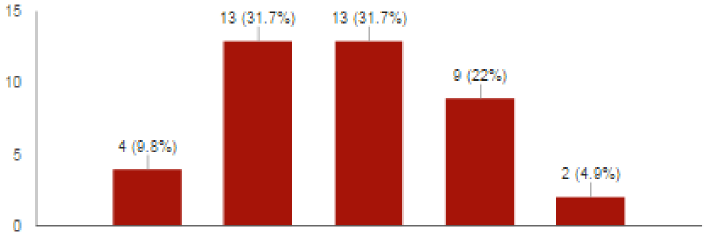
The vehicle responded to my actions in a way I expected (41 responses)



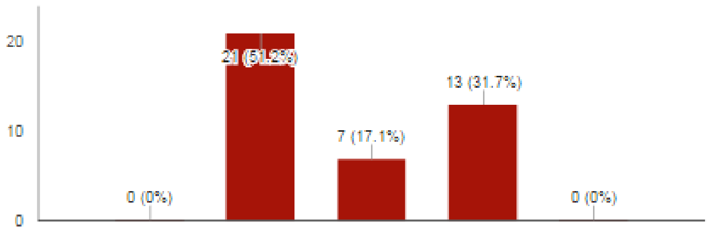
Driving in the virtual environment seemed consistent with my real world experiences (41 responses)



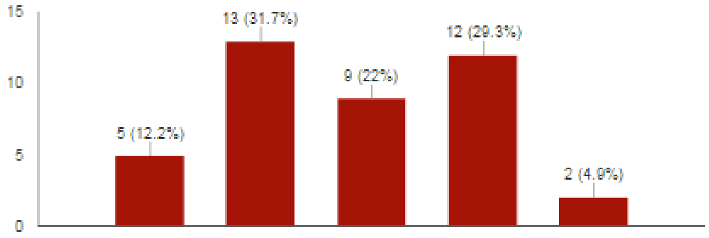
Traffic behaved in a realistic way (41 responses)



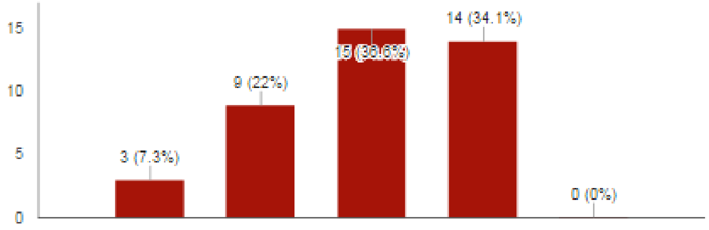
The vehicle I drove behaved in a realistic way (41 responses)



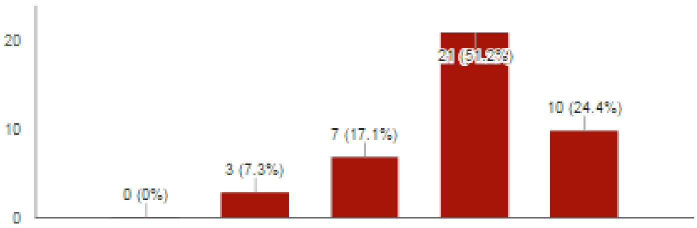
The behaviours of other cars seemed realistic (41 responses)



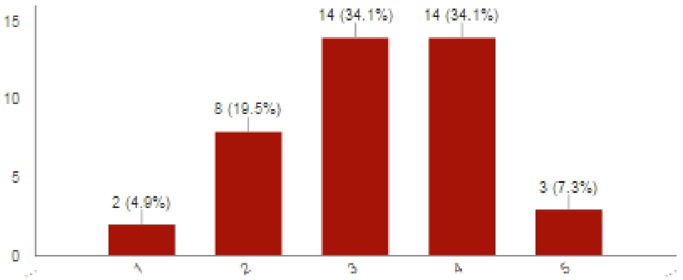
The actions I performed in the car seemed consistent with the real world
(41 responses)



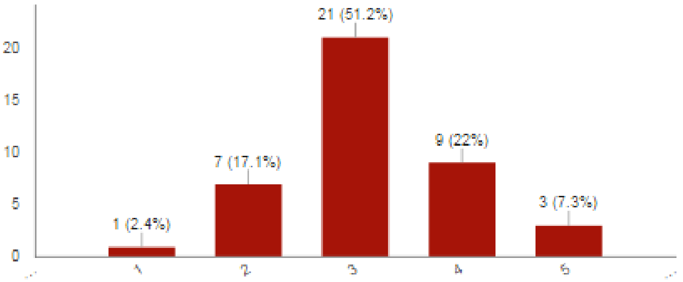
The roadway and roadway traffic system seemed natural (41 responses)



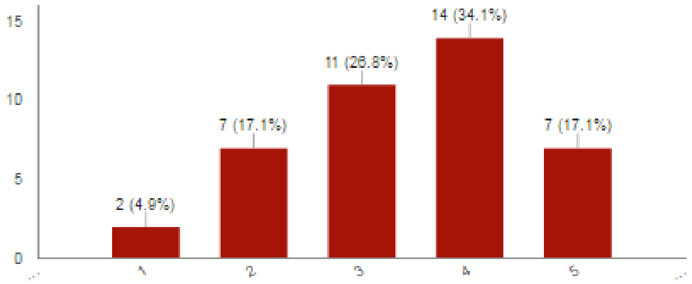
Events which occurred during the drive seemed realistic (41 responses)



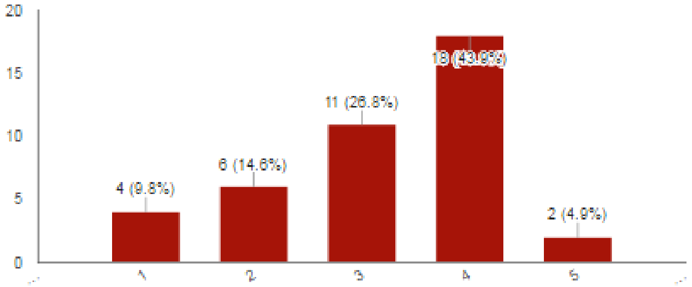
The drive seemed natural and believable to me (41 responses)



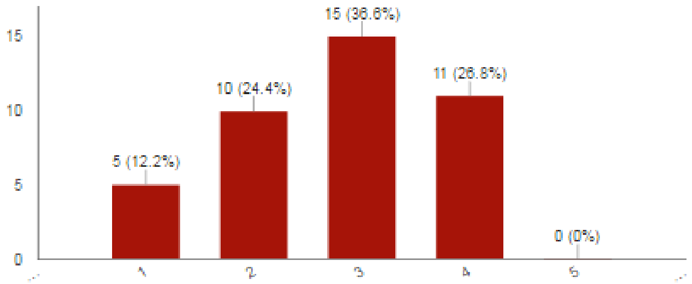
I felt as if I had been on a journey (41 responses)



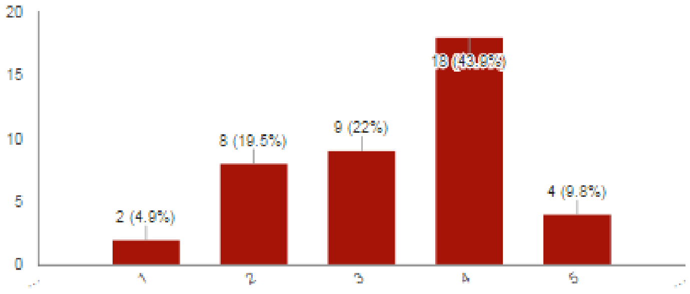
I had a sense of driving on a real road (41 responses)



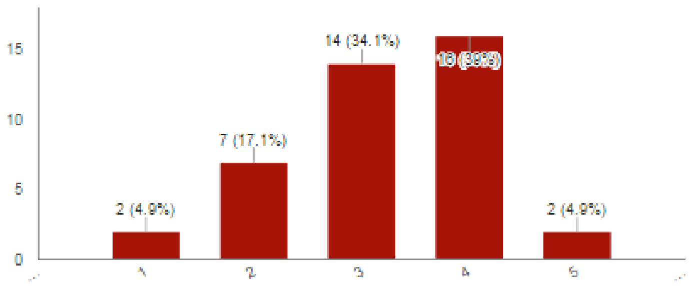
I felt that the displayed environment was part of the real world (41 responses)



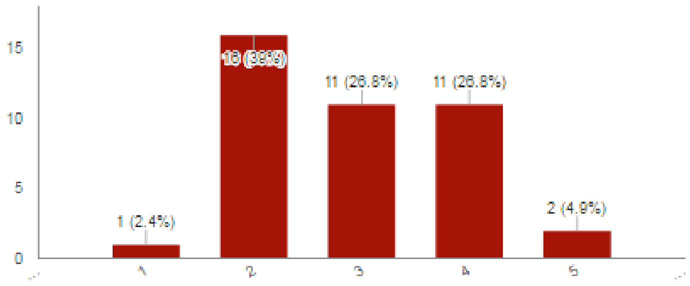
I sensed that the vehicle was actually moving (41 responses)



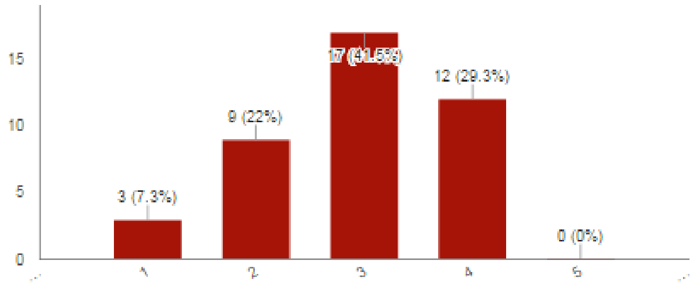
I had a physical sensation of the vehicle being on a road (41 responses)



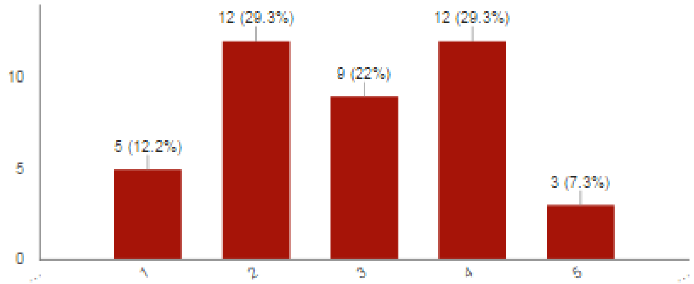
I felt as if I was in a laboratory (41 responses)



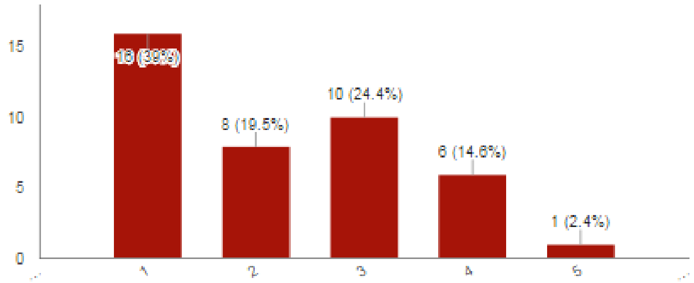
I felt I was in the same space as the roadway, road traffic systems and the environment
(41 responses)



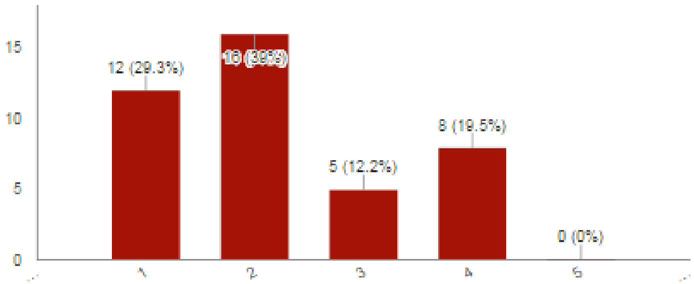
I sensed I had travelled from one place to another (41 responses)



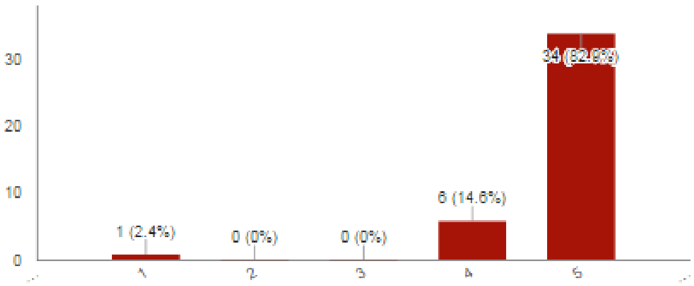
I felt the vehicle could breakdown (41 responses)



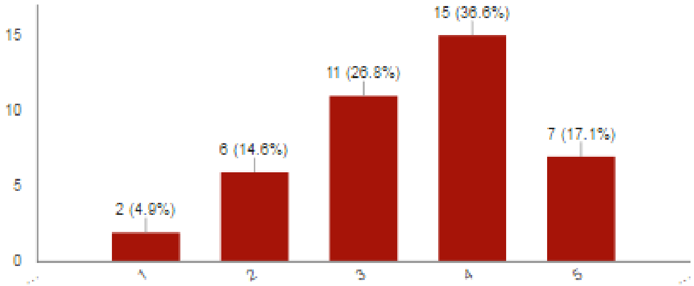
I had a sense of control over events outside the vehicle during the drive (41 responses)



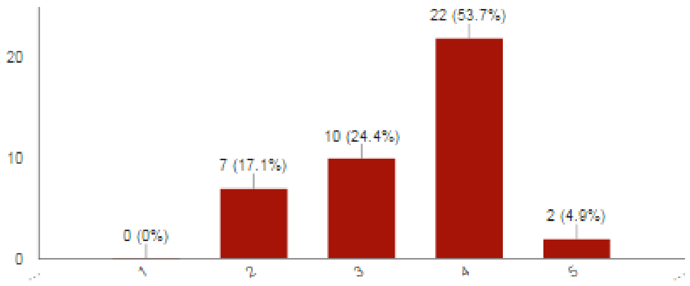
I made driving errors that I don't make in real driving (41 responses)



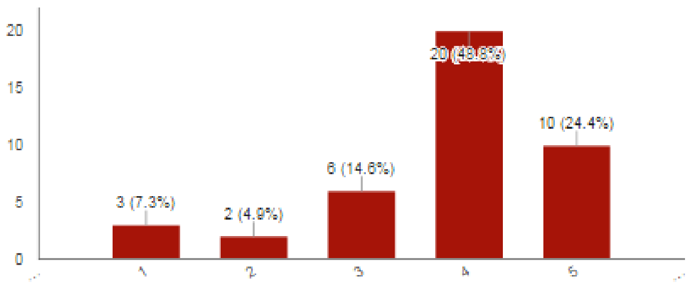
I had a sense of sounds coming from within the vehicle (41 responses)



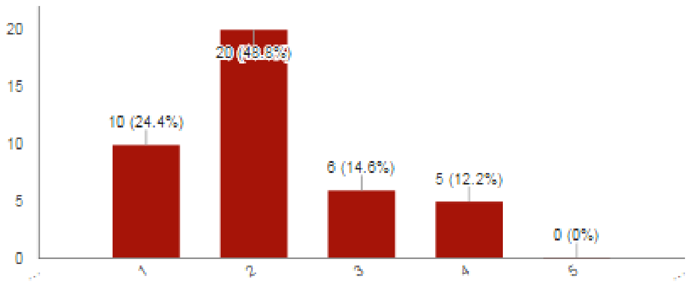
The quality of the displayed environment increased my awareness of driving the vehicle
(41 responses)



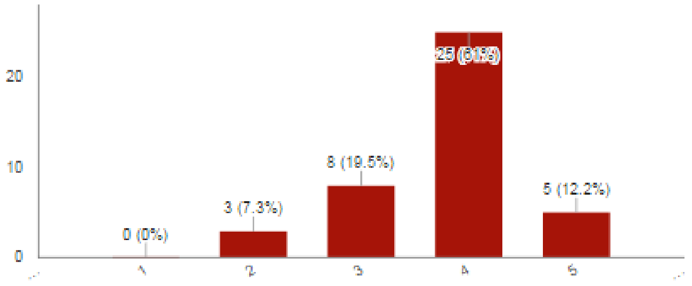
The auditory information such as engine and road noise improved the experience
(41 responses)



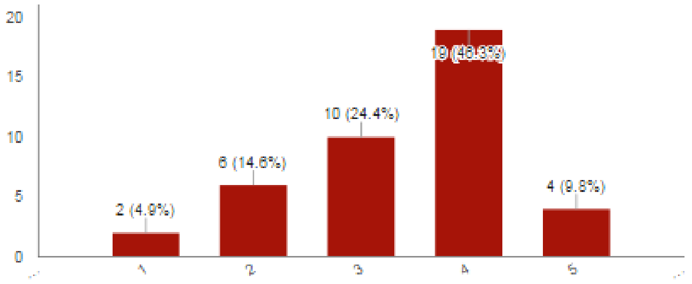
I felt I was just watching something (41 responses)



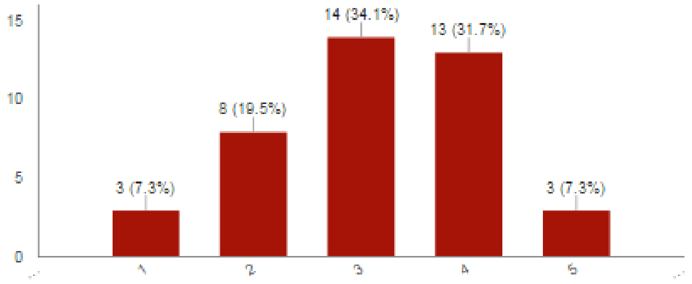
I sensed that time had passed (41 responses)



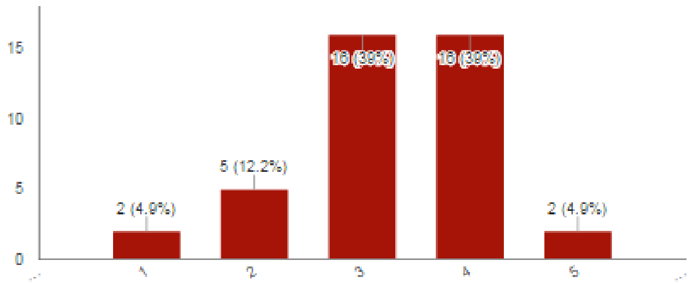
I felt drawn into the driving environment (41 responses)



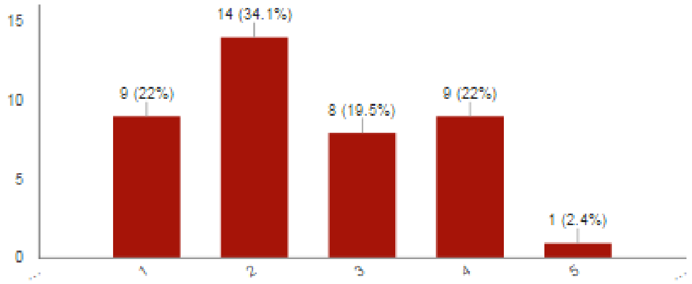
I became completely immersed in driving the vehicle (41 responses)



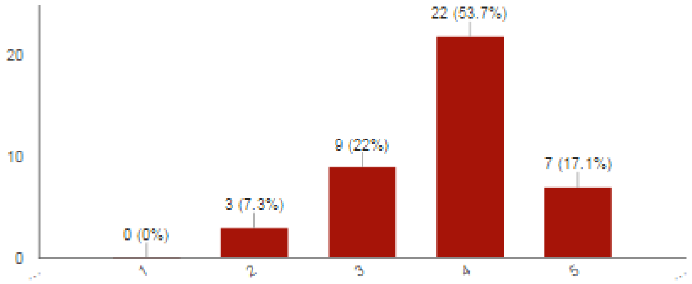
I felt surrounded by the virtual driving environment (41 responses)



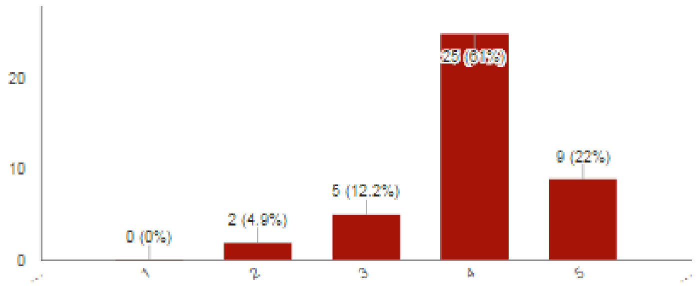
I felt as if I was sitting in a real car (41 responses)



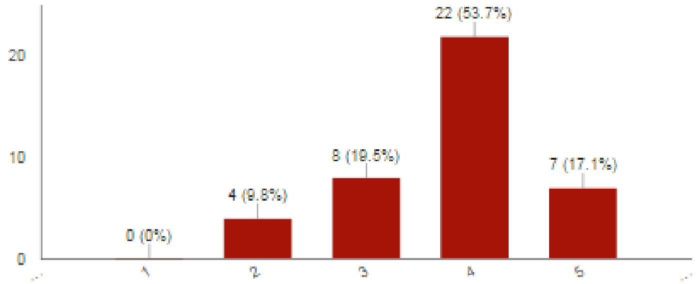
I reacted to critical situations on the road (41 responses)



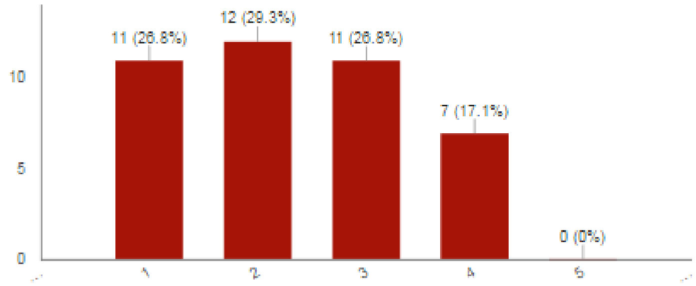
I reacted to threatening situations on the road (41 responses)



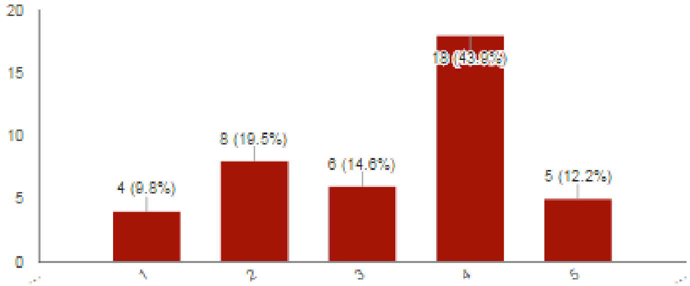
I felt compelled to react to obstacles on the road (41 responses)



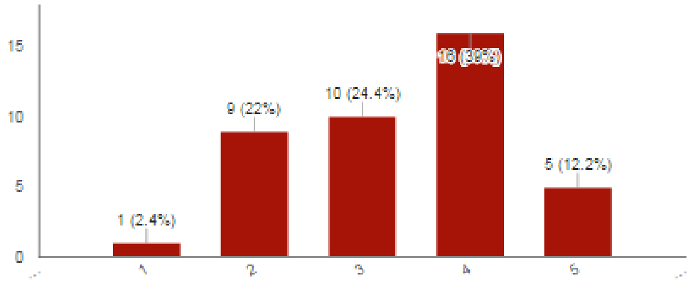
I felt scared during hazardous situations (41 responses)



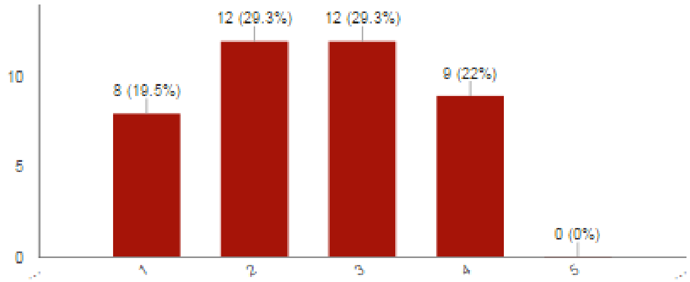
I was worried that I might crash the vehicle (41 responses)



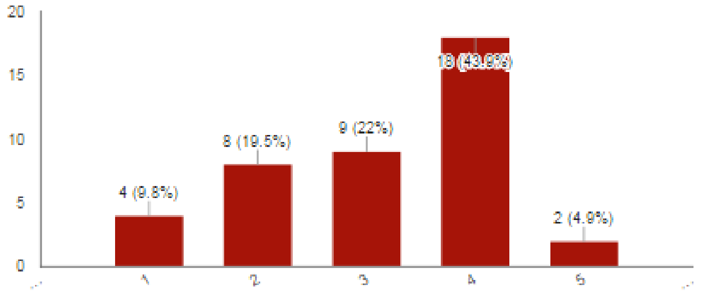
I was compelled to obey the displayed road signs and symbols along the route
(41 responses)



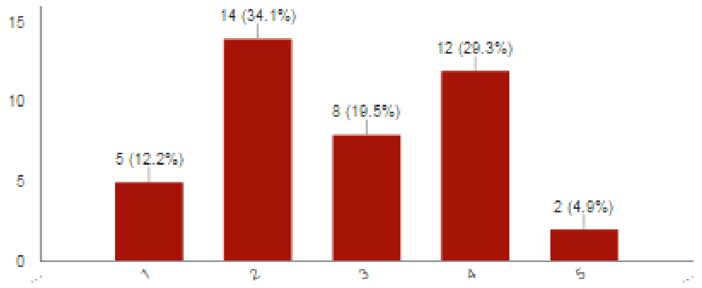
The movement of the vehicle seemed natural (41 responses)



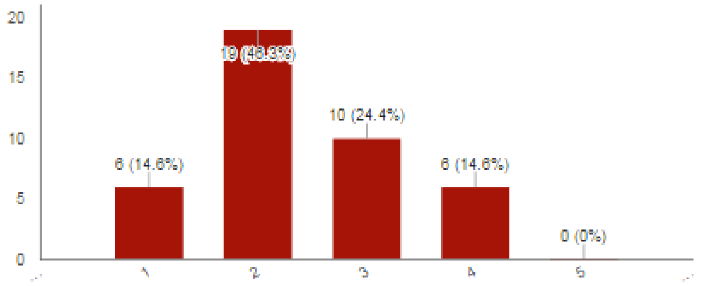
I had a sense of physically controlling the vehicle (41 responses)



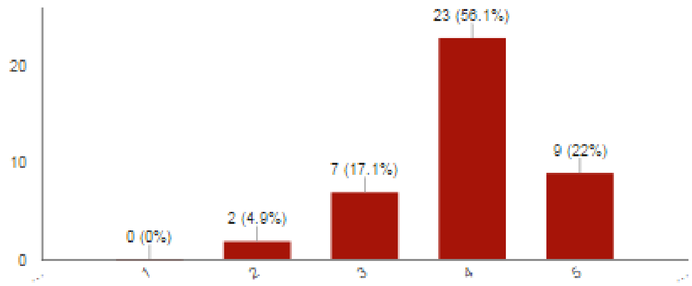
I felt I could judge my current speed (41 responses)



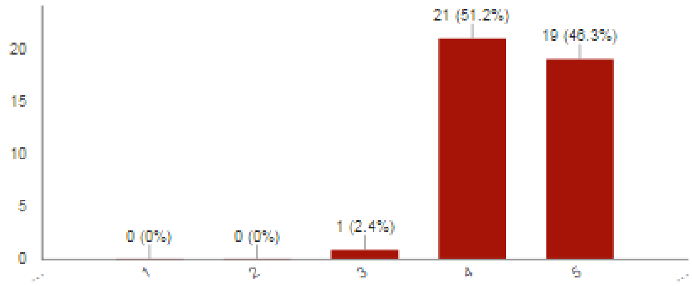
I could reliably judge the distance between the vehicle and other vehicles (41 responses)



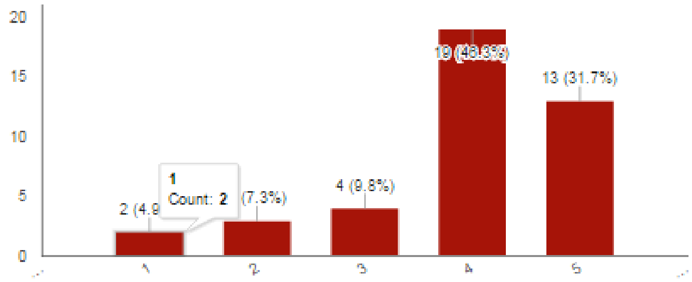
I was aware of the traffic (41 responses)



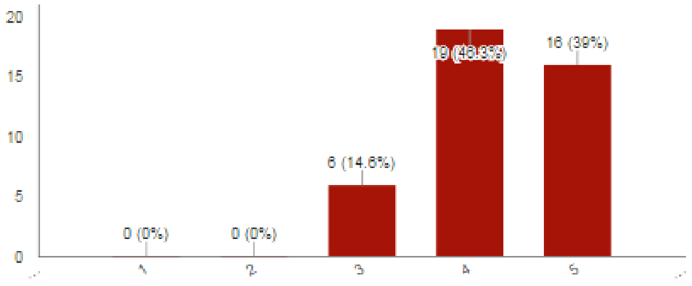
I had to concentrate when driving (41 responses)



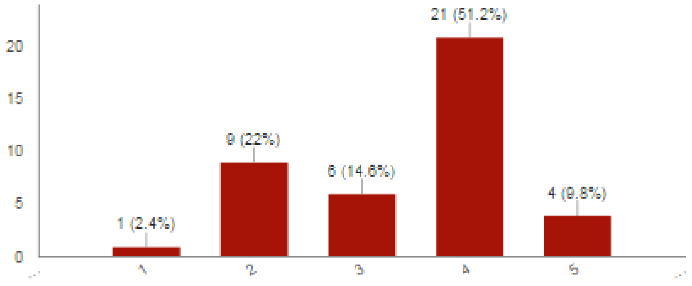
I paid more attention to the road environment than I did to my own thoughts (41 responses)



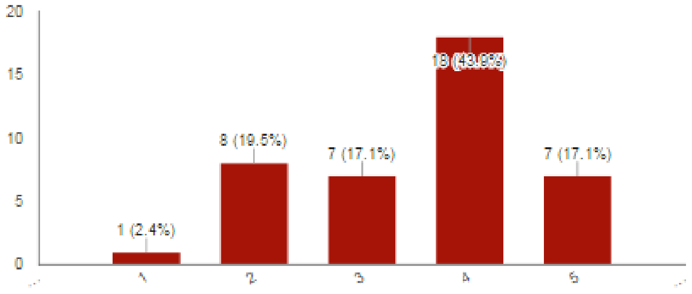
I prioritised driving the vehicle over other tasks (41 responses)



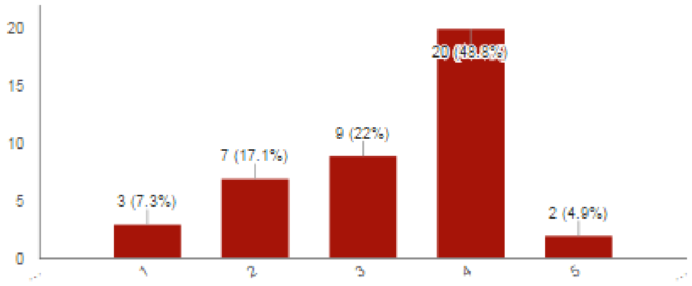
I was aware that other people were driving cars around me (41 responses)



The driving scene depicted could really occur in the real world (41 responses)



I was checking all around me during the drive (41 responses)



I remembered it was a computer program (41 responses)