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Master of Transportation Sciences

Master's thesis

The use of variable message signs to facilitate merging maneuvers at highway on-ramps - a driving simulator study

Ruben Kuipers

Thesis presented in fulfillment of the requirements for the degree of Master of Transportation Sciences, specialization Traffic Safety

SUPERVISOR :

Prof. dr. Tom BRIJS

MENTOR :

Mevrouw Nora REINOLSMANN

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Preface

This document is the result of the work done for the master thesis to complete the master of transportation science at the University of Hasselt. The aim of this thesis to determine how people react to systems using variable message signs in merging zones, in a Flemish context. To do so, a driving simulator study on the effects of variable message signs on headway distances, mean speeds, and lane changes in the so-called merging zones was conducted.

The first part of this document focusses on what actually makes a merging maneuver unsafe. This section gives an insight in which factors contribute to the level of safety for the different parties involved. First, the merging maneuver for the merging driver is discussed, followed by the merging maneuver from the point of view of the drivers on the highway. Special attention is given to merging on short on-ramps at the end of this first section. This chapter profides information on which aspects need to be addressed when trying to make the merging zone a safer part of the highway network.

The current measures which are used to increase the safety in merging zones are described in the second part of this document. These different solutions have their or pros and cons when it comes down to increasing the safety in the merging zones. The measures are compared to the known safety issues which became clear in the first part of the literature review. Based on these findings a solution is proposed which has the best potential to actively solve the safety issues in the merging zone.

The third part of this document describes how drivers perceive variable message signs and guidelines for using variable message signs. The part focusing on the perception is divided into the detection, identification, decision, and response mechanism related to road signs. These results are then used as the basis for the design of the intervention which is tested during this study.

The final part of this document consists of a description of the results of the driving simulator study and a descriptive analysis of the outcome of the post-drive questionnaire. This section provides information on how people reacted to the different designs which they were exposed to in the driving simulator study, and how they perceived the different designs.

I would also like to use this time to show my gratitude to Nora Reinolsmann for her help and guidance during this period, as well as all the people at IMOB who assisted in the programming of and setting up the driving simulator study. I would also like to thank the individuals who the time to take place in the study, as there would be no results without participants.

"Research is formalized curiosity. It is poking and prying with a purpose."
Zora Neale Hurston (1891 – 1960)

Summary

Traffic safety is a worldwide issue, affecting people on a daily basis. The highway is considered to be a relative safe traffic environment, compared to the urban areas. This is mainly due to the small differences in speed between cars and the fact that all vehicles travel in the same direction. There is however one part of the system which results in friction and interaction between vehicles at different speeds and directions, the merging zone. This thesis focusses on the safety of these merging zones and examines methods to increase the safety of road users in these merging zones by influencing traffic on the through lane by means of variable message signs.

The literature indicates that one of the major safety aspects of merging zones is the differences in speed between the traffic on the highway itself and the merging traffic, as well as the available gap for drivers to merge into. A secondary aspect is the effect of lane changes to yield for merging drivers, which have a disruptive effect on the traffic flow and increase the risk of accidents. All of these aspects are relatable to the traffic on the through lane of the highway, meaning that is it possible to mitigate these problems by influencing drivers on the highway.

Different strategies can be used to increase the safety in merging zones, ranging from extending road markings to actively influencing traffic. The method found to be the best fit for the stated safety issues is gap metering. Gap metering actively influences traffic on the highway to create gaps for merging traffic to utilize using variable message signs to persuade drivers to leave a gap for the merging vehicle. This thesis, therefore, focuses on the effects of this measure on driving behavior of people on the through lane of the highway, by making use of a driving simulator study. Three different designs were tested in this study, as well as combinations of these designs with variable speed limits. The designs differ in how abstract they are and in which motion a pattern flashes, with the flow of traffic and against the flow of traffic.

41 participants successfully completed the study. A repeated measures MANOVA and repeated measures and one-way ANOVAs and were used to determine the effects of these different measures on the speed, headway, and lane choice of drivers in the merging section. Results of this driving simulator study showed that there is no significant effect on the mean speed, mean headway distances, or the lateral position of drivers as a result of gap metering signs being in place. The significant results found were caused by the distance driven in the scenarios. Pairwise comparisons showed that driving behavior was relatively similar to that of the base condition for all other scenarios.

A post-drive questionnaire revealed that people find both design types which were tested to be understandable. When asked if they have a preference for a certain design type, opinions were balanced among the group of participants. When asked if participants noticed a difference in the flashing patterns, a large majority stated to not have noticed such a thing. This indicates that there is no “right” design for a gap metering sign between the two which were tested. Participants were asked whether or not gap metering has a benefit to road safety in their opinion and if they would adhere to the instructions given. The large majority of the participants stated to both see an use for gap metering to increase safety, and to be willing to adhere to the given instructions.

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1. Introduction

The European Union reported that, in 2016 alone, 25.500 people lost their lives as a result of road accidents in the EU (European Commission, 2017). This number is even higher when looking at the worldwide number of road accident fatalities, worldwide around 1.25 million people die every year in traffic accidents. (World Health Organization, 2017)

When addressing safety based on road type, the highway is a relative safe traffic system compared to other road types. In the UK for example, when comparing highways to rural roads, it showed that highways carry 20% of all traffic compared to 40% for rural roads. However, when looking at the distribution of crashes, highways accounted for only 6% of the total number of road fatalities, compared to 62% for rural roads. (Department for Transport, 2015)

One of the reasons for this, relatively, high safety is the lack of interactions between traffic streams, except for the areas around on-ramps. These form sources of interactions which results in accidents between two conflicting traffic streams competing for the same road space. (Kondyli & Elefteriadou, 2009) (Sun, Li, & Sun, 2015) These on-ramps form a crucial component of the highway, as they are the points of entrance to the system. The competition for road space is potentially made more severe if the acceleration lane of the on-ramp is short and/or does not transfer into the hard shoulder, leaving no run-off area for the vehicle on the on-ramp and adding stress for the driver.

This interaction between the two traffic streams takes place in the so-called merging section (Figure 1), which is a major source of vehicle collisions on highways according to multiple studies (Yang & Ozbay, 2011) (R. Liu, 2011) The merging section consists of the through lane, on which highway traffic is driving, and the acceleration lane on which the merging vehicle comes up to speed before merging into the through lane (Figure 2).

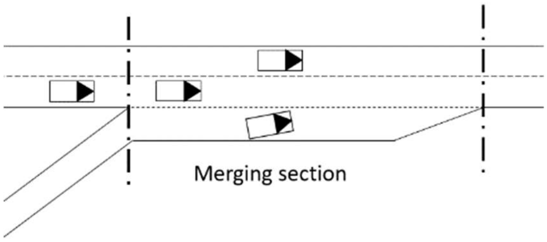

Figure 1 Merging section on a highway (source: own image)

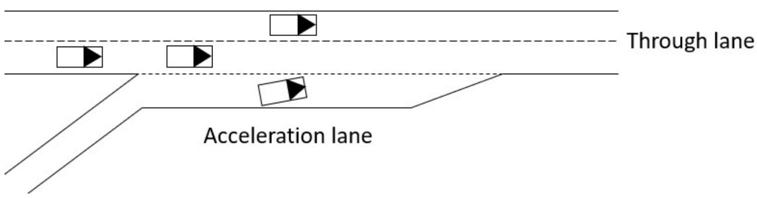

Figure 2 Design elements of the merging section (source: own image)

It is important to note that not only the drivers on the through the lane and the acceleration lane have an interaction during the merging maneuver, but the drivers on the through lane itself interact with one another due to lane changes as well. When a vehicle merged into traffic the driver has to adjust their speed and headway to the traffic stream it finds itself in. The surrounding drivers have to make speed and headway adjustments as well to accommodate the merged driver. These headway- and lane changes can also have a negative impact on traffic safety.

Kononov, Durso, Reeves, & Allery, (2012) state that the increased crash rate as a result of flow disruptions on highways could be due to a compression of the traffic flow, or increased density, without a reduction in speed. Zhou & Sisiopiku, (1997) state that the chance of multivehicle accidents increases as a result of the increase in conflict when the traffic density increases. This increased risk of accidents is due to the short headways, which leave too little time and space for drivers to react accordingly.

A study in the United States by Cassidy and Rudjanakanoknad (2005) showed a decrease in traffic flow as a result of lane changes near on-ramps. The researchers also state that the traffic flow in the adjacent lanes, next to the outer right lane, is disrupted by lane changes. This phenomenon can be explained when looking at the fundamental theory of traffic flow which states that “at any point of the road the flow q (vehicles per hour) is a function of the concentration k (vehicles per mile)”(Lighthill & Whitham, 1955). In relation to lane changes, this means that the concentration in one lane is increased by the vehicle changing lanes, thus decreasing the flow in that lane.

In order to increase the safety on highways, there is a necessity to examine strategies to decrease the risk of accidents in these merging zones. The risk of accidents potentially increases when the length of the on-ramp is reduced and there is no run-off area available for the driver. However, it is not always possible to increase the length of the on-ramp, due to spatial constraints for example. In these cases, other measures to ensure the safety of all road users have to be implemented. One of these potential strategies is the use of dynamic variable message signs. The safety benefit from these dynamic signs is a result of the ability to deliver real-time messages to drivers about upcoming hazards such as accidents, congestion, weather conditions, and lane closures. (Lai, 2010)

Variable Message Signs (VMSs) are traffic control devices, which are used to provide information to the road user. The signs can be programmed to show certain messages depending on the type and use of the sign, one example of the use of VMSs are variable speed limits as seen in Figure 3.

Figure 3 Variable speed limit on A4, The Netherlands. Source: (Rijkswaterstaat, 2013)

This study aims to determine how speed and headway choice can be influenced, making use of a VMS strategy in order to increase the safety in merging zones. In the next part of this document the mechanisms influencing the safety of merging zones, current strategies which are used to increase the safety in merging zones, and the perception of VMSs are described. An explanation of the study set up is given in the latter part of this document. The study uses of a driving simulator study in which the driving behavior of people is tested when exposed to different strategies.

2. Literature review

The following chapter explains the relevant findings from the literature review. First, the safety issues in a merging zone are explained, followed by current known solutions used to increase the road safety in merging zones. The final part of this chapter explains what variable messages are and how people respond to these types of signs.

2.1. What makes a merging zone unsafe

The merging zone at an on-ramp is a crucial component of the system, as it forms the point of entrance for drivers to join traffic on the highway. The interaction of multiple traffic streams, driving behavior, and the geometry of the roadway make the merging zone a dynamic environment, with an increased workload for drivers. (Wang, Hu, & Zhang, 2016)

Riener, Zia, Ferscha, Ruiz Beltran, and Minguez Rubio (2013) outline various phenomena to be considered when looking at merging traffic based on an observational study. Three of these phenomena are relevant for this study due to their relation to traffic safety:

- (some) through lane drivers are not aware of the ramp ahead, resulting in lane changes at the last moment;
- many drivers are afraid about late merging;
- drivers are scared if requested to change into a small gap.

With regards to traffic safety, the first phenomenon can lead to disruptions in the flow of traffic due to sudden lane changes, and the latter two can lead to dangerous situations on the acceleration lane when a vehicle slows down instead of performing the merging maneuver and on the through lane when performing a so-called forced merger (this is explained later on).

A study on the types of ramp-related accidents in Northern Virginia (US) showed that the most commonly reported types of accidents on the entrance ramps were sideswipe/cut-off and rear-end crashes. The first is caused when drivers are in the process of merging into through lane traffic, the latter occurs on the on-ramp itself. (McCartt, Northrup, & Retting, 2004) Similar crash types are stated by Li, Xiang, Ma, Gu, and Li, (2016) to be the most common in merging zones in their microsimulation study making use of surrogate safety measures.

Jin, Fang, Jiang, DeGaspari, & Walton (2017) stated that the key issue concerning the safety for the merging vehicle is the lack of sufficient gaps for drivers to join into the highway traffic, which is in line with the most common types of crashes. A complimenting factor is the speed differences between the vehicles on the through lane and acceleration lane, a study in France showed differences as much as 30km/h between both traffic streams. (Louah, Daucher, Conde-Céspedes, Bosc, & Lhuillier, 2011)

The next two sections will further explain the mechanisms involved in the merging maneuver from the standpoint of the driver of the merging vehicle, and drivers of the vehicles on the highway.

2.1.1. The merging maneuver for a merging driver

A driver tasked with merging into highway traffic will accelerate and merge into the outside lane of the highway when there is enough room to do so. If there is a vehicle present in the adjacent lane, the merging driver must decide whether to merge ahead of behind of this vehicle (C. Liu & Wang, 2012) and make speed adjustments according to this decision. These speed adjustments and the act of gap searching make the merging maneuver a task demanding situation for the merging driver. (Chu, Miwa, & Morikawa, 2014).

Michaels and Fazio (1989) defined five tasks the merging driver is faced with when entering the highway. 1. ramp curve tracking, 2. steering transition from ramp to acceleration lane, 3. acceleration, 4. gap search, and last (depending on the available space) either 5a. Steering transition from the acceleration lane to the highway or 5b. abort. This indicates that the merging driver is faced with constantly changing and demanding task during the maneuver of merging into traffic. The task demand of a traffic situation can be described as the complexity of the task. The relationship with traffic safety is based on the individual's capabilities to cope with the task demand (Fuller, 2000), but it is safe to state that a more demanding task leads to an increased risk of accidents for road users.

One of the most important steps of the merging maneuver is the process of gap searching which can be defined as "a driver looking for an acceptable gap in which he/she feels it is safe to merge into the traffic stream". According to Riener et al., (2013) drivers are scared when asked to merge into small gaps. The actual gap, in this case, is defined by the distance between the front end of the trailing vehicle and the rear end of the leading vehicle on the target lane (Nobukawa et al., 2016). Figure 4 shows a schematic explanation of the gap.

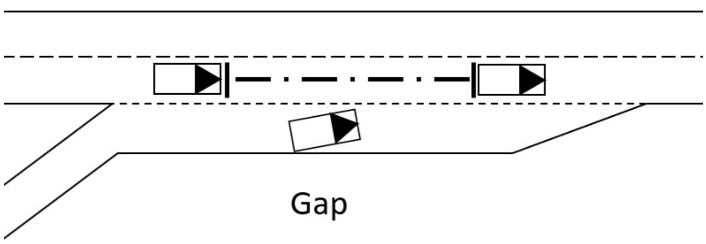

Figure 4 Gap when merging. Source: own material

Three types of merging maneuvers based on the available gap can be identified of which the latter two result in interactions between the merging driver and the drivers on the highway. (Kondyli & Elefteriadou, 2011)

Free merge	-	No interaction between the merging vehicle and the vehicle on the highway
Cooperative merge	-	The driver on the highway yields or slows down in order to create a gap for the merging vehicle
Forced merge	-	The merging vehicle initiates a merging maneuver and the driver on the highway has to respond

The available gap also has a relation with the location where drivers merge. A study in the Netherlands used video data to determine the locations on the acceleration lane at which people tend to perform the merging maneuver. The results of the study showed that when the road is not congested people tend to merge at the beginning of the acceleration lane. This situation can be identified as the 'free merge'. However, when the traffic volume on the main road is higher, the number of late mergers increases. This has to do with a process known as 'gap acceptance'. When the traffic volumes are higher a driver is less likely to find a large enough gap, thus he/she stays in the acceleration lane for a longer time. (Daamen, Loot, & Hoogendoorn, 2010)

The process of gap acceptance is based on the driver assessing the available gap on the adjacent/target lane. The driver of the merging vehicle will make a judgment on whether or not to change lanes on the available gap. The smallest accepted gap is known as the 'critical gap'. The size of this critical gap depends on the driver itself, the traffic characteristics, and the road. (Marczak, Daamen, & Buisson, 2013) The smallest accepted time (or critical) gap for a driver merging into the through lane traffic lays between 0.75s and 1.0s according to the study conducted in the Netherlands. The size of the minimal accepted gap decreases the closer a driver gets to the end of the acceleration lane. (Daamen et al., 2010)

Once a driver has successfully merged into the traffic stream, their attention must switch from gap acceptance to headway assessments to the vehicle in front. As stated before, the smallest accepted gaps are between 0.75s and 1.0s, this results in a time headway which is shorter than the safe car following distance which is defined as 2s. (SWOV, 2012). Thus, when a driver is forced to accept a smaller gap due to congested traffic conditions, the driver is placed in a dangerous situation.

It is safe to say that a driver will try to create a safe headway distance after merging onto the highway. Meaning that if the merging driver accepted a gap smaller than 2s, he/she will slow down or change lanes in order to create a time headway of at least 2s. This process is known as relaxation (Daamen et al., 2010) (Zheng, Ahn, Chen, & Laval, 2013) and potentially leads to oscillations in the traffic flow due to decelerating drivers. As stated before, these disturbances increase the risk of accidents and conflicts as the density increases.

The effect of short acceleration lanes

If the acceleration lane does not transfer into the hard shoulder, a driver of a merging vehicle is required to execute a mandatory lane-change maneuver along a limited length of a merge lane in these (Yang & Ozbay, 2011), leaving less room for mistakes and adding to the stressful and task demanding situation. In the case of a short acceleration lane and a vehicle in the adjacent lane, the driver might not be able to find an acceptable gap ahead or behind within the given space of roadway. (C. Liu & Wang, 2012)

A longer acceleration lane does not always mean easier and safer merging maneuvers, however. A study in France showed that if a vehicle completes the merging maneuver near the end of the on-ramp, their speed decreased in order to adjust for the available gap. The speeds measured at the end of the on-ramp were similar to 100 meters before the end. (Louah et al., 2011) A driving simulator study by Calvi & De Blasiis (2011) observed that the behavior of a driver during merging maneuvers is significantly influenced by traffic volumes of the through lane traffic and that the acceleration lane length did not show any significant effect on the speed, trajectories, and acceleration of drivers. These findings indicate that a longer on-ramp does not result in easier merging perse, since vehicles are capable of reaching a sufficient speed before reaching the end of the available road space, but that the available gap is the most important.

A focus group study by Kondyli & Elefteriadou (2009) found that drivers stated to be more aggressive when a tapered design is used for the on-ramp, meaning that the accelearion lane does not transfer into the hard shoulder. This aggression not only leads to higher acceleration rates but can lead to forced merging behavior as well. This happens when the merging driver cannot find an acceptable gap over the entire length of the on-ramp, and the driver has to “push their way into traffic”. Drivers on the through lane have to accommodate for the merging vehicle through lane changes or speed adjustment to avoid accidents when this happens. (Fatema & Hassan, 2013)

This forced merging occurs when the lane change becomes urgent and there is no clear space for the merging vehicle to use. Toledo, Koutsopoulos, & Ben-Akiva (2007) provide the following example for a situation where a driver performs a forced lane change: in Figure 5 “car A wants to move into the right lane. The speeds of A and C are similar, the lane change may not be completed until it becomes urgent. At that point, car A will force its way to the right lane”.

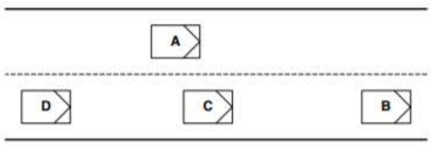

Figure 5 A forced lane changing situation. Source: (Toledo et al., 2007)

A study in the US into the risks of lane changing stated that the task of changing lanes requires drivers to divide their attention between different aspects of the driving task, the same as with merging drivers. Whilst preparing for a lane change, drivers are tasked with monitoring the forward roadway, their surroundings, steering the vehicle, regulating the vehicle’s speed, and using the turn signal. The researchers stated that “drivers who are pressed to change lanes may exhibit degraded performance in one or more of these subtasks.” (Fitch et al., 2009) The act of a forced merge at the end of an on-ramp can be considered to be a situation in which a driver is pressed to change lanes. The driver of the merging vehicle can neglect to perform a task at a sufficient level, resulting in a higher risk for accidents.

The forced merging action can also lead to the driver on the through lane having to decelerate or make a lane change when the merging vehicle forces its way into their path, which in turn can result in shockwaves in the flow of traffic. (Toledo et al., 2007) (Fatema & Hassan, 2013)

2.1.2. The merging maneuver for a through lane driver

Just as the drivers merging onto the highway, the drivers who are already in the through lane are faced with complex driving tasks. Drivers need to respond to several situations at the same time while simultaneously maintaining a high speed. These situations include maneuvering, reading road signs, route planning, and maintaining a safe distance from other maneuvering vehicles. This demands high levels of cognitive responses to ensure the safety in merging zones. (Hossain & Muromachi, 2013)

Research into the behavior of drivers on the through the lane with regards to merging zones is slim, however. A study using focus group meetings by Kondyli & Elefteriadou (2009) showed that when people are driving on the freeway they prefer to make a lane change to facilitate the merging vehicle over reducing their own speed to create a gap. This result was based on stated preference and might not reflect their actual behavior. A later study by Kondyli & Elefteriadou (2012) investigated behavior by using video recordings at highway merging sections. This study confirmed the findings of the focus group meetings that people are more likely to change lane than to decrease their speed in order to allow the merging vehicle to join on the highway.

An observational study on driving behavior near on-ramps in Tokyo showed that vehicles on the through lane tend to either force a lane change to the outermost lane before reaching the merging zone or when in the merging zone itself, in order to avoid the interaction with the merging vehicles.. (Sarvi, Kuwahara, & Ceder, 2007) This behavior can be classified as "(courtesy) yielding"

Kita (1999) states that a typical situation where this yielding behavior is observed is 'low-speed merging situations'. These are situations in which the speed of the merging car is lower than that of the vehicles on the highway. And whilst such voluntary actions can help with reducing the risk of merging conflicts, they can also cause problems when other drivers who are not willing to change lane, or are not expecting another driver to make a lane change to allow a courtesy yield (Jin et al., 2017). More importantly, these situations require sufficient space on adjacent lanes for the driver to change their lane in order to create a gap for the merging vehicle. A driver on the through lane might no longer be able to facilitate the merging vehicle by changing lanes when intensities increase.

Another safety risk is explained by Riener et al., (2013). The researchers stated that it is possible that a driver might not be aware of the presence of the on-ramp and makes a late (sudden) lane change in order to yield for the merging vehicle. This sudden change of lanes can, in turn, lead to unsafe situations as it disrupts the flow of traffic and other drivers might not always be aware of this possibility and have to suddenly adjust their speed.

Cruise control habits on highways

Not everyone on the road makes use of cruise control whilst driving, and it is possible to state that everyone has different habits when driving on the highway. This is of interest for this study since a large part of the relevant driving task is based on the "tactical level" meaning that these are semi-automatic mechanisms, this includes gap and speed maintaining. (Michon, 1985) If a driver is used to the cruise control to take over one of these tasks, it is possible that their behavior changes. As studies have shown that the use of cruise control has an effect on different aspects of the driving task. (Larsson, 2013) (Rajaonah, Tricot, Anceaux, & Millot, 2008)

Furthermore, results of a study on driving behavior with adaptive cruise control showed that drivers who were used to driving with adaptive cruise control drove less safe in situations where they could not use adaptive cruise control, compared to a group of non-users. (Bianchi Piccinini, Rodrigues, Leitão, & Simões, 2014) The variables tested where the mean driving speed and two different headway values.

For this study, this is relevant, even though the driving simulator does not offer cruise control. The assumption, with regards to driving behavior in merging zones, is that people who are used to driving with cruise control assistance respond differently to the gap metering sign since their habits differ to that of non-users. In this case, the results of any analyses regarding the effect of gap metering, with the variable "cruise control habit" can lead to insights of possible different reactions by both groups. No assumptions are made on whether or not the group who have a habit of using cruise control drives safer or not.

2.2. What are the current measures used to increase the safety in merging zones?

The previous chapter revealed that the most important issues when it comes to road safety in the merging zone are the lack of gaps, the difference in speed, and the disturbances as a result lane changes. This chapter explains different, known, strategies to increase the safety in merging zones at on-ramps which have been tested before or are currently in use around the world. Some of these strategies focus on traffic on the through the lane and some focus on the traffic on the on-ramp itself. The four strategies which are discussed in this chapter are:

- Continuous marking
- Ramp metering
- Variable speed limits
- Gap metering

2.2.1. Continuous marking

Continuous marking on the left side of the acceleration lane prevents drivers to make an early merge. There is no literature on the safety aspects of this strategy to the knowledge of the author. An attempt has been made to contact national road agencies of countries who make use of this kind of road markings. In Sweden this kind of marking is known as 'observation distance' and the aim is to allow drivers to adjust their speed and their gaze on the through lane traffic. There is no known research on the safety implications of this kind of marking in Sweden however. (Trafikverket, 2018) In the Netherlands, this kind of marking is solely aimed to increase the throughput of traffic in these locations, and no research has been conducted on the safety aspects. (Rijkswaterstaat, 2018)

2.2.2. Ramp metering

Ramp metering is used to reduce the number of vehicles entering the highway by stopping them on the on-ramp, and letting the vehicles "drip" into the stream of traffic one-by-one (sometimes two at a time). The system measures the traffic intensities and speeds on the highway using detection loops for example. If the intensity reaches a predefined threshold the system is automatically turned on, if the intensities drop below this threshold the system is turned off again. (Kennisinstituut voor Mobiliteitsbeleid, 2012) Figure 6 shows a schematic representation of a ramp metering system.

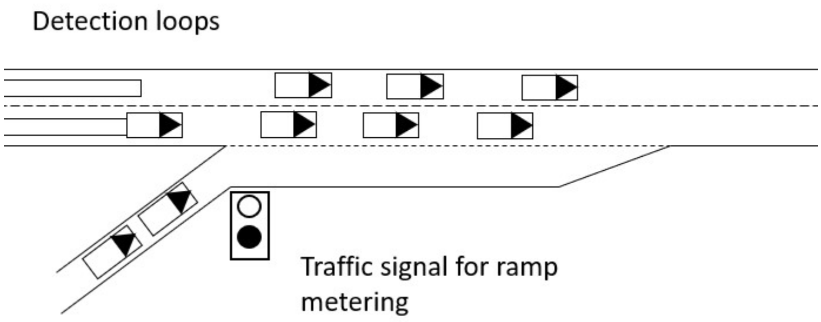

Figure 6 A schematic representation of a ramp metering system. Source: own material

A study in the United States by (C. Liu & Wang, 2013) on the safety effects of ramp metering systems found that the average reductions on freeway collisions near an on-ramp exit after installing a ramp metering system were around 36%. The authors state that most of the reduced collisions belong to the property damage only category, however, a 36% reduction shows the significant safety benefit of ramp metering.

However, the system does not control traffic on the highway itself (Lu, Varaiya, Horowitz, Su, & Shladover, 2010). Ramp metering only limits the number of vehicles entering the system, but it is not aimed to help in creating the necessary space for vehicles to actually merge into. Another downside of this system is the risk of blockages on the surrounding road network if the demand on the on-ramp is too high and exceeds the discharge rate of the system (Cook, Pretty, & Cleveland, 1970) (Cambridge Systematics, Inc, 2001) (Nevada Department of Transportation, 2013).

2.2.3. Variable speed limits

Variable speed limits (VSLs) are realized by displaying speed limits on variable messages signs in most cases (Figure 7), this system is initiated as a response to current traffic conditions. The variable speed limits have an advantage over the traditional static speed limits in that this system can be adapted to the traffic conditions such as congestion, weather, and dangerous situations on the highway. (Ma, Yang, Liang, & Li, 2015)

Figure 7 Variable speed limit on A4, The Netherlands. Source: (Rijkswaterstaat, 2013)

A study by Carlson, Papamichail, Papageorgiou, & Messmer (2010) stated that the safety effect of VSLs is due to the speed reduction, and the speed homogenization of the traffic stream on the highway. The researchers stated that during a multiyear evaluation of the safety impact of VSLs a reduction of 20% to 30% of accidents were recorded after the implementation of the VSL system.

Similar observations were made in different studies into VSLs. Lower speed differences between consecutive vehicles, speed variation, and frequency of short headways were observed in these studies (Nissan & Koutsopoulosb, 2011) which also result in a more homogeneous flow of traffic and an increase in the safety on the highway. Similar findings are shown a driving simulator research on the effect of dynamic speed limit systems on the homogeneity of driving speeds by van Nes, Brandenburg, and Twisk, (2010)

A study in the UK showed an estimated decrease of 10% in the number of accidents with injuries, and a decrease of 20% in the ratio of damage only accidents for every injury accident. This research also states that these reductions are a result of the uniform speed and headway distances. Furthermore, the researchers state that due to the VSLs the lane distribution and utilization even out, meaning that all lanes are used in a more effective manner and the number of lane changes was reduced. (Highways Agency, 2004)

With regards to merging zone safety, the reduction in speed means that the speed differences between traffic on the highway and the merging traffic are reduced. This allows for merging drivers to merge into traffic with the same speed, without having to accelerate in an 'extreme fashion' on the acceleration lane.

A downside of using this system with regards to saver merging zones is that there are no gaps created in the traffic stream for merging drivers to use. Even though short headway distances decrease, a slower traffic stream does not automatically mean that the gaps between vehicles increase. Furthermore, a study on VSLs on highways in the Netherlands by Smulders (1990) showed a decrease in the headways on the right lanes, which means that the actual gaps decrease.

2.2.1. Gap metering

Gap metering is a variation on 'ramp metering'. However, where ramp metering focusses on the traffic on the on-ramp, gap metering focusses on the traffic on the through lane. The most common method to do this is the use of variable messages signs above the through lane of the highway. Figure 8 shows a schematic representation of a system which makes use of gap metering. The most right lane on the highway is closed, in order to free up road space for the merging stream of vehicles from the on-ramp. This system would require enough spare capacity on the highway to allow for a temporary lane closure.

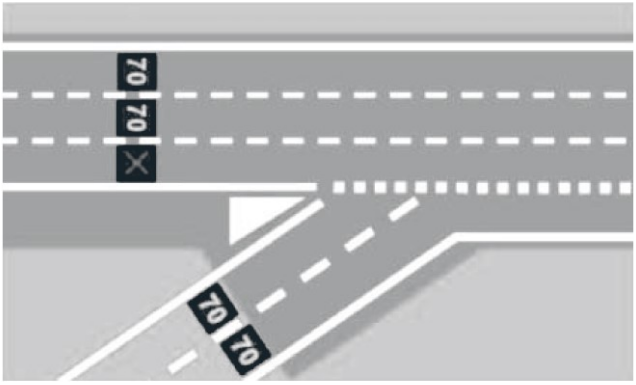

Figure 8 Gap metering. Source: ("Freeway Geometric Design for Active Traffic Management in Europe," n.d.)

A study by Jin, Fang, Jiang, DeGaspari, and Walton (2017) used VISSIM simulations to model the effects of gap metering on highways. In their study, they made use of a system which indicated that drivers should leave a gap on the most right lane for other drivers to merge into, so not a mandatory lane change as shown in Figure 8. The sign they proposed showed an image explaining the suggested maneuvers to the drivers, as well as two flashing beacons to indicate if the system was active (Figure 9).

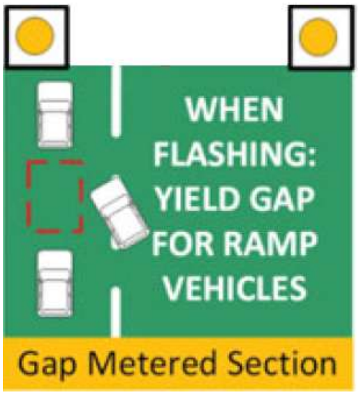

Figure 9 Sign suggested by Jin et al., (2017)

The study showed the importance of the compliance rate for this system. If the number of people complying with the instructions increased, the capacity of the intersection increased. There was, however, no link made with the traffic safety in these areas. The authors do state that the system has an increased risk of causing congestion upstream because of to the reduced capacity due to lane closure or traffic being slowed down. (Jin et al., 2017) A potential downside to this system is the disruptions in the traffic flow due to drivers slowing down and or changing lanes.

Gap metering shows the most potential to actively target the safety issues in the merging zone as stated before. It will, therefore, be the main part of this further research. There is however little knowledge about the reaction of drivers to such a system when implemented on the highway.

2.3. Variable Message Signs

It became clear from the previous chapter that gap metering is, potentially, a good measure to increase the road safety in merging zones. Gap metering is considered to be a Variable message sign (VMS). These signs are a programmable traffic control system which can be located at important locations on the highway network. In order to understand how a VMS influences traffic and driver behavior, it is important to understand how drivers react to the information. However, as the literature review showed, the current scientific knowledge on the effects of VMS on driving behavior in merging zones of highways in relationship to traffic safety is slim.

Therefore, “traditional” traffic signs are assessed as well based on relevant characteristics (e.g. location criteria) since visual performances do not differ significantly between both types of traffic signs. (Koppa, 2001) This paragraph shows international guidelines on the use of VMSs and explains how people respond to the messages on the signs as well as potential pitfalls when designing a VMS strategy.

2.3.1. Guidelines on the use of Variable/traffic message signs on highways

Different government bodies have constructed several guidelines on the design and location of traffic signs and variable message signs on highways. These guidelines state the desired design of the message which is shown and the best location to place a sign on the highway. This paragraph highlights some of the guidelines.

Message design

The Dutch agency for road design guidelines (CROW) states that the use of symbols to display a message in a VMS is more desirable than the use of text due to familiarity and attentive effect of the sign. The message which is shown should be centralized on the signs itself. However, when multiple messages are shown, in the case of multiple exists, for example, the message should be placed on the side where the action should be taken. E.g. a message showing information on an exit to the right should be displayed on the right side of the sign. (CROW, 2017)

Location

Different guidelines from different countries show different minimum distances to place a VMS or gantry signs on highways near junctions. It is therefore difficult to state the optimum location where a VMS should be placed.

The State of New York Department of Transportation (2011) state that the signs should be positioned in a way so that drivers have time to (1) detect the sign (2) read and comprehend the message (3) initiate a response and (4) make an appropriate decisions based on the information gained from the message. Based on the cited MUTCD Guidelines a minimum distance of 793 meters (2,600 feet) is mentioned for visibility and 244 meters (800 feet) for the legibility of the sign.

Guidelines by both the government of British Colombia and the Netherlands state that gantry signs related to exits and junctions need to be placed starting at 1200 meters before the junction itself, and repeated at 600 meters. (British Columbia. Ministry of Transportation and Highways., 2000) (Rijkswaterstaat, 2017)

2.3.2. Driver's reaction to variable message signs

The reaction to a situation (or stimuli) can be divided into four different processes. This process can also be used to understand how drivers perceive variable message signs, or "traditional" traffic signs when driving on the road. First, the driver has to perceive the stimuli, followed by identification. After a driver identifies the stimuli, an emotion/response is triggered and the driver has to make a decision. The final step of this process is the actual response to the stimuli and the execution of the necessary action. (Olson, 1989)

Detection

An important aspect of the detection is the location of the stimuli, this either occurs in the field of vision, meaning that the driver does not need to constantly 'scan' in order to identify the stimuli. Or this stimuli occurs outside of the field of vision, meaning the driver has to actively scan for the stimuli. This scanning process puts a strong cognitive load on the driver, meaning that he/she has less time to focus on the actual driving task. Murphy & Greene (2017) state that when a task has a high perceptual load (stimuli outside of the field of vision, or an unclear message for example), the perceptual capacity of the driver is used to a high extent. This leaves less (or no) room for additional stimuli to be processed. When the perceptual load is low, the opposite effect is the case. This indicates that if a driver has to actively scan for a traffic sign, the spare cognitive capacity is lowered and he/she can focus less on other driving tasks.

The relationship between the placement of a VMSs and the effects on traffic safety has not been the subject of much research. Most research into the location of VMSs focusses on the effect of travel time messages on the diverging behavior and route choices of drivers.

A study in Italy examined drivers gaze and recollection of vertical road signs which are located next to the road. The results of their study showed that only 25.06% of vertical signs were looked at by the drivers. The authors state that a possible reason for this low number is that the vertical signs are not located in the driver's field of vision when driving on a road, as drivers tend to focus on their lane and less on their surroundings. (Costa et al., 2014)

Identification

A driving simulator study by Mollu et al., (2016) looked into the difference in comprehension of directional signs placed on cantilevers (placement next to the road), and gantries (placement above the road). The results of this study showed that, with the same fixation time, signs placed on gantries are easier to understand than those on cantilevers.

A large part of the identification is based on the message which is displayed, such as the format and color (as cited by Mollu et al., 2016). A VMS can display both graphical and textual messages or combinations of both. Figure 10 shows several examples of the available ways to show information on a VMS. The choice between the use of text or symbols has a relationship with the understandability of the message which is shown.

1. 

2. 

3.

Figure 10 Examples of variable message designs Symbol (1), text (2), and a combination (3) Source: (Arbaiza & Lucas-Alba, 2012)

Just as with “traditional” traffic signs, it is important to make sure that the message displayed on the sign focus on both maximizing the understandability and minimizing the time necessary to read it (Dutta, Fisher, & Noyce, 2004) (Jeihani, NarooieNezhad, & Bakhsh Kelarestaghi, 2017), this is especially important in merging zones where the driver cannot diverge its attention for a prolonged period of time.

Studies on the understandability of traffic signs have shown that there are three important ergonomic factors to keep in mind using traffic signs to change behavior in traffic. According to Ben-Bassat & Shinar,(2006) these three factors are:

Compatibility - the location of the sign and the association with the displayed message

Familiarity - the extent to which a driver is familiar with the sign as a result of prior experience

Standardization - the extent to which the colors, shapes are consistent with the majority of traffic signs

A study in the US on human factors issues related to reading and comprehending variable message signs concluded that providing familiar standardized messages and employing symbols will help drivers to understand traffic signs better. Short messages that minimize memory requirements can also potentially be helpful. (Proffitt & Wade, 1998) Shinar and Vogelzang (2013) also state the importance of familiarity with the designs of a sign. When replacing the symbol signs with text signs (with a similar message) the familiarity became irrelevant in the perception of the message. The CROW[1] states a similar approach, suggesting signs which are easy on the eyes and use standardized symbols which increases the understandability of the message. (CROW, 2017)

Kline, Ghali, Kline, & Brown (1990) studied the relationship between distance and perception of traffic signs. The results showed that the understandability of signs making use of symbols is better at a greater distance compared to signs using text. Contradicting these findings, research by Shinar and Vogelzang (2013) surprisingly found that text signs were better comprehended and the comprehension time (based on the reaction time) was also shorter compared to signs using symbols. The researchers do state that both text and symbols signs were shown at the same distance, thus not taking the perception with relation to distance into account and that in real-world driving it is likely that symbol signs will be perceived from a greater distance.

A study measuring the comprehension time of signs in Austria made use of interviews to test new signs to be placed at work zones on the highway, the signs indicated mandatory lane change at that point and instructions to keep their lane and merge later. The latter sign is stated to be new to Austrian drivers. The different instructions were shown in a graphical and textual sign. (Hössinger & Berger, 2012) The results state that signs indicating a mandatory lane change are easy to understand for drivers when shown in a graphical manner. The researchers state that this is mainly due to the familiarity with this kind of instruction on the highway. The sign instructing to merge late are new. The graphical signs performed poorly during the test (meaning a higher comprehension time), compared to the textual signs. Textual signs proved to be understood quicker when the number of letters was lower. (Hössinger & Berger, 2012)

The researcher state that if a symbol sign does not comply with the three ergonomic rules, the additional text should be used to clarify the message. The use of ‘text only signs’ is however not desirable due to the internationalization of today’s world. As cited by Nygårdhs (2011) the use of multilingual message signs should be limited as much as possible due to the potential to overload drivers with information.

Decision

A study by Luoma, Rämä, Penttinen, and Anttila (2000) reviewed the “non-measurable” effects from field observations of a study on messages warning drivers for slippery road conditions and minimum headways, such as changes in drivers’ focus. The researchers interviewed drivers who encountered the signs, making use of roadside interviews.

The results of the study show that drivers who were influenced by the VMSs changed their focus of attention toward finding cues of potential hazards, testing the road slipperiness, and resulted in more cautious overtaking behavior. The authors state that these effects were not limited to a certain group of drivers, thus the use of VMSs is accepted by all types of drivers.

[1] A Dutch technology platform for transport, infrastructure and public space.

Lee and Abdel-Aty (2008) conducted a study on how drivers respond to various types of dynamic traffic information and VMSs under different traffic conditions, using a driving simulator. 86 participants drove a 5-mile highway section on which three different warning messages were displayed. The results of the study imply that warning messages and reduced speed limits should be displayed upstream the area of interest. The authors also recommend that speed reduction is gradually and that the speed limits downstream of the area of interest should be increased to meet the desire to compensate for lost time. The latter also helps to reduce a buildup of congestion due to the locally lowered speed limits.

Response

A field study on the effect of VMSs showing messages warning drivers for slippery road conditions and minimum headways was conducted in Finland. The signs warning for these slippery road conditions made use of a combination of graphics and text (showing the minimum distance in meters). The driving behavior was monitored 536-1.800 meter upstream and 360-1.100 meter downstream of the VMSs. The signs were turned on when the road conditions were judged to be slippery by an operator. (Rämä & Kulmala, 2000)

The results of this study showed a reduction in the speed of 1-2 km/h and a reduction in the number of time headways shorter than 1,5s. However, further away from the VMSs this reduction was lower and no longer significant. The effect was also greater at night and when the sign was flashing, based on this the authors argue that the signs are more effective when they are more conspicuous. (Rämä & Kulmala, 2000) However, based on a previous study cited by the authors, the use of flashing lights does not always have a positive effect.

2.4. Conclusion

The complexity of the traffic situation in a merging zone makes it hard to single out one cause for possible incidents, as several factors interact with one another. Based on the literature, it can be stated that the cause of an increased risk of accidents in merging zones for all drivers can be found in a combination of the task demands, the sudden increase in density when a vehicle merges on to the highway, and the disturbances to the flow of traffic due to lane changes and headway adaptions by drivers.

Comparing the most common types of accidents to the known behavior of drivers with regards to merging zones it shows that both the speed differences and the available gap in the traffic stream on the through lane are the instigators of the unsafe situations for the interaction between the merging vehicle and through lane traffic. Studies showed that drivers state to be more aggressive in their merging behavior when the acceleration lane is perceived to be short. If the available gap is not large enough, but the end of the acceleration lane is near, drivers tend to force their way into the through lane traffic, increasing the risk for sideswipe/cutoff accidents and disturbances to the flow of traffic. It is also stated that drivers are scared to merge into small gaps and/or at the end of the acceleration lane, which can lead to unsafe traffic maneuvers.

If a driver does decide to merge into the smallest acceptable gap, he/she merges into a gap with an unsafe time headway. The critical gap is stated to be less than the safe headway distance of 2s. The drivers then have to adjust their headway by slowing down (relaxation). The process of relaxation results in disturbances in the flow of traffic.

The merging maneuver is not the only action which cause these disturbances in the traffic flow. It was stated that drivers which are already on the highway prefer to change lane to yield for merging vehicles. This however results in different interactions, and disturbances in the traffic near/in merging zones. In a safety perspective this interaction cannot be neglected, even though it is a secondary effect of the merging maneuver.

Studies into the length of the acceleration lanes showed that the effects are not significant to the merging behavior of drivers. The traffic volume, and the resulting available gaps are shown to be more important for safe merging than the length of the acceleration lane. The short length does, however, induce forced merging and adds stress to the drivers' task.

Different strategies are known to potentially increase the safety in merging zones, ranging in technicality and abilities. The literature review revealed that the difference in speed between the traffic on the through lane and the merging vehicle, as well as the available gap are the main risk factors in merging zones. When these risk factors are put next to the counter measures which are currently used, it becomes clear that some of these measures do not solve the mentioned safety issues.

Continuous road marking, does not actively influence the flow of traffic. Ramp metering does actively influence the amount of traffic merging onto the highway, but does not contribute to the creation of gaps or speed homogenization. Variable speed limits do contribute to decreasing the difference in speed between the merging vehicle and traffic on the through lane. It does however not contribute to the major issue, the available gap to merge into.

This is where gap metering shows the most potential to solve the known issues when it comes to the safety of merging zones. Gap metering is designed to actively create gaps in the flow of traffic on the right-hand lane, and thus solving the problem of insufficient gaps. There is however little research in the driver's reaction to such a system.

Gap metering makes use of a variable message sign (VMS). The literature shows that the use of symbols is the most desirable design when making use of VMSs to increase the safety in merging areas. This is due to the general ease of understanding, the better understandability at greater distances compared to text is especially important for signs on the highway. The design of the symbols has to be understandable for road users and it is best to make use of familiar symbols according to the literature. It is however also stated that the understandability of new signs is hard to predict, and it is beneficial to accompany these signs with a textual message indicating the desired behavior.

Signs placed next to the road showed to take longer to comprehend. Researchers state this is mainly due to the sign not being in the field of vision for drivers. Signs placed on gantries above the roadway solve this problem, since the signs are placed in the field of vision of the drivers. Studies into the compliance of VMSs have shown that drivers change their behavior due to messages are shown in VMSs, it is however also stated that it is important that the sign is placed within the right context. A warning message next to the sign for example, increases the compliance of drivers.

The gap metering sign must therefore be placed in the right context, near enough to the on-ramp itself, the design must use recognizable images, and a textual message must be present to help with understanding the message.

3. Design of the gap metering system

Three different designs for the gap metering sign are tested during this study (Figure 11). The first sign is based on the designs used by (Jin et al., 2017) in their VISSIM study. The design for the other two signs shows two flashing chevrons to indicate the necessity to create a gap. These two designs differ in the direction which the chevron flashes. The first 'chevron-sign' shows the chevrons flashing against the flow of traffic (from the top to the bottom) whereas the second sign shows the chevrons flashing with the flow of traffic (from the bottom to the top). The actual direction of the chevron itself did not change

A study in the Netherlands on the effect of directional arrows on highway gantries on drivers' speed examined the effect of the direction of the arrows. The study found out that if these directional arrows are positioned against the flow of traffic, instead of with, a decrease of 10km/h occurs. (Molenkamp, 2008) The chevrons flash in opposing directions to investigate if this effect can be used with regards to gap metering.

Important for the designs is to maintain a level of familiarity to make them easy to understand for drivers on the highway. (Proffitt & Wade, 1998) (Shinar and Vogelzang 2013) Signs making use of chevron markings are also used in other situations, and the final design was inspired by these signs. This helps to ensure a certain degree of familiarity. A text message, in Dutch, explaining the desired behavior is located underneath the graphics to help enhance the comprehension of the signs. This is in line with findings from different researchers on the use of graphical and textual traffic signs. Stating that graphical signs are more easily understood when familiar, but novelty signs require a short textual message to help drivers to understand the desired behavior. (Hössinger & Berger, 2012) (Shinar & Vogelzang, 2013) The message translates into "Leave space".

Square design	Chevron flashing from top to bottom	Chevron flashing from bottom to top
		

Figure 11 The three different gap metering sign designs. Source: own material

Figure 12 shows a SketchUp model of the gantry sign. The choice to place the gap metering signs on a gantry is based on the results of a driving simulator study by Mollu et al. (2016) into the difference in comprehension of directional signs placed on cantilevers (placement next to the road), and gantries (placement above the road). This study showed that, with the same fixation time, signs placed on gantries are easier to understand than those on cantilevers. Furthermore, A study in Italy examined drivers gaze and recollection of vertical road signs which are located next to the road. The results of their study showed that only 25.06% of vertical signs were looked at by the drivers. The authors state that a possible reason for this low value is that vertical signs are not located in the driver's field of vision. Drivers tend to focus on their lane and less on their surroundings when driving. (Costa et al., 2014)

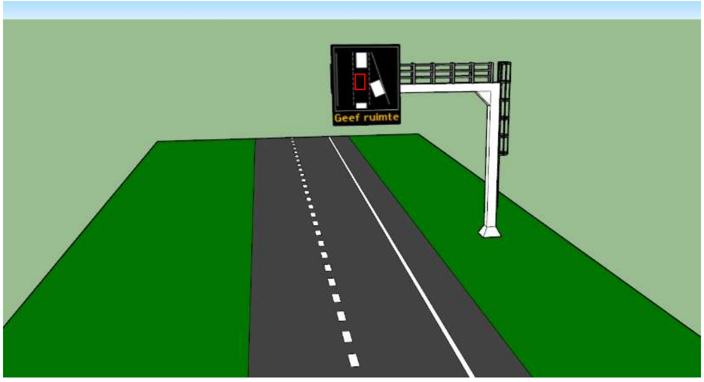

Figure 12 SketchUp model of the gantry with gap metering sign as used in the driving simulator study. Source: own material

Static chevron markings were placed on the roadway itself when the gap metering signs with chevron markings were placed. These static road markings help to indicate the necessary space one should give once presented with the gap metering sign to the drivers. The gap between the static road markings was set at 45 meters which is according to the guidelines for the use of chevron markings (Agentschap Wegen en Verkeer, 2014). Hwang and Park (2005) stated 32.7 meters to be the accepted gap in non-congested situations, and Daamen et al. (2010) stated 1 second to be the gap which was accepted (which converts to 33 meters at 120km/h).

This gap is well within the 45 meters of space in between the chevron markings, meaning that it is possible to state that merging drivers will accept the gap when mainline traffic maintains a distance of two chevrons. The sign with a square indicating that drivers have to leave a gap is not indicated by any feedback in the form or road markings. This is a limitation of such a design, as it is not normal to have "boxes" on the road surface, and the actual placement is also difficult, in contrast with chevron markings.

4. Research questions

Problem statement

The merging zone poses a complex, dynamic, situation in which multiple parties interact on an ever-changing basis. The main aspects which have a negative effect on the overall safety in merging zones are the differences in speed, but more importantly the lack of sufficient gaps in the stream of traffic for merging drivers to safely merge into the traffic on the highway. A secondary issue, from a safety perspective, are the interactions and disturbances in the traffic flow as a result of drivers changing lanes to yield for the merging vehicle.

Gap metering offers a potential solution to solve the main safety issue by actively persuading drivers to create space for merging drivers. Little is known however on the effect of such a system on driving behavior from the perspective of drivers on the highway and if additional measures, such as a reduction in speed, are necessary to allow for safe operating on highways.

Objectives

The objective of this study is to determine the effect of gap metering with regards to increasing the safety in merging zones. This is achieved by determining the effect of different gap metering systems on the driving behavior of drivers on highways in merging sections based on three research questions.

Research question 1

"Does the design of the gap merging sign influence the headway distances of drivers?"

The study makes use of two different design styles, a red box indicating to leave space and chevron marking to indicate the desired headway distance. In the first design, there is no clear indication of the distance, as it shows to leave enough space for a vehicle to merge but it does not show how much this would be. The latter does have this feedback. Both designs can have a different effect on driving behavior.

Hypothesis: chevron markings are easier to understand for road users and result in larger headways, due to the indication of distance.

Research question 2

"Are there differences in speed and headway distances when variable speed limits are put in place to support the gap metering system?"

The literature indicated that the speed differences and available gap are the main reason for accidents in merging zones. The combination of both a gap metering system and a variable speed limit makes sense from this perspective, but it also adds more signs on the road. This makes it interesting to see if and how the variable speed limit influences the effects of the gap metering system.

Hypothesis: the use of variable speed limits has a positive effect on gap metering systems.

Research question 3

“Does the pattern in which the chevron markings flash change the headway distance and speed of drivers?”

The chevron markings can flash either with or against the flow of traffic. The first pattern shows a flowing motion whereas the latter shows a more withholding motion. This difference in perceived motion of the sign can potentially influence headway and speed choices.

Hypothesis: chevron markings flashing against the flow of traffic result in lower speeds and larger headways.

5. Methodology

The methodology for this study is explained in this chapter. The tools which were used, as well as the design and the procedure of the experiment, are explained.

5.1. Data collection

The study made use of a medium-fidelity, fixed-base driving simulator, shown in Figure 13. The simulator uses a 180° seamless, curved screen with a resolution of 1024 × 768 pixels and a frame rate of 60 Hz to display the scenarios to the participants. The simulator is equipped with a force-feedback steering wheel, and a brake-, clutch-, and accelerator pedal. The mirrors, rear-view, and side-view are projected on the screen and audio of the vehicle, traffic, and the environment is present through an external speaker. The simulator makes use of 'STISIM drive 3' software to run the simulation and collect data for the predefined parameters. (Ariën et al., 2015)

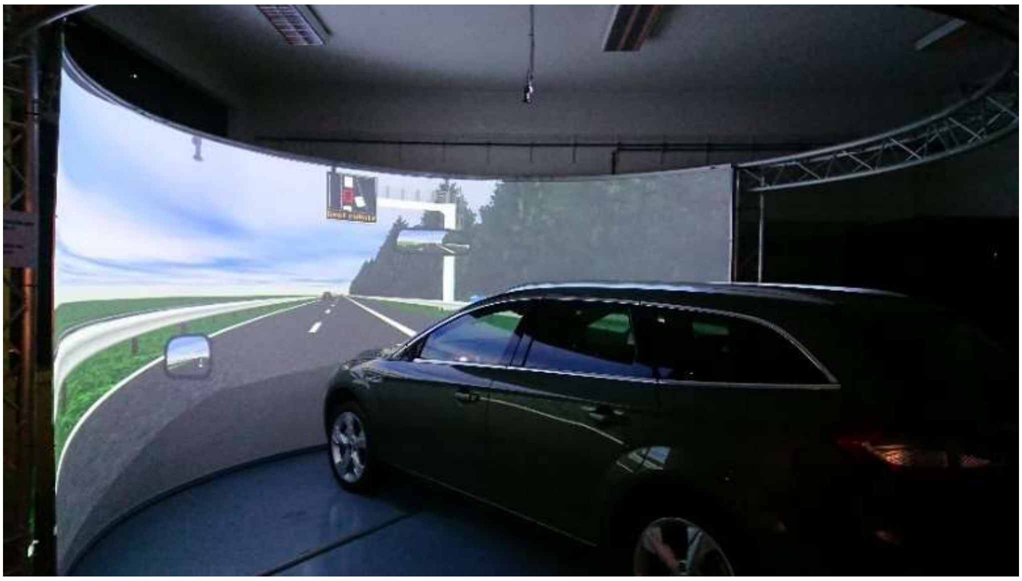

Figure 13 Driving simulator at IMOB. Source: own material

The driving simulator is chosen for this study since it can be used to place drivers into difficult situations at a high crash risk without exposing them to harm. Additionally, it allows for full control of the situational factors such as weather and traffic intensity, for the exact same scenario for every participant, and helps to give insight into driver performances. (Caird & Horrey, 2011)

A risk when using a driving simulator, however, is the difference in perception of speed, distance, and movement in a driving simulator compared to real-world experience. (Caird & Horrey, 2011) This can pose a problem since an important aspect of this study is the headway choice by drivers. A study by Risto and Martens (2014) on the difference between headway choice in real-road driving and driving simulator driving showed that there is no significant difference in the chosen headway between real-world and simulator driving. These findings indicate that a driving simulator is a valid tool for this specific research.

5.2. Design of the scenarios

Figure 15 shows an overview of the design for both the scenarios with and without variable speed limits. The actual merging zone uses the same dimensions for both of the designs. This allows for a direct comparison of the difference in parameters between gap metering with and without variable speed limits. The analysis zone is indicated in red, this is the area which is of interest for all of the analyses later on. The distances at which the signs are shown are relative to the start of the on-ramp, e.g. the gap metering sign is placed at 250 meters upstream from the beginning of the on-ramp.

The general road design, dimensions, and traffic characteristics are similar in each scenario. This is done an attempt to reduce the number of variables which can potentially alter the results to a minimum. The only changing variable in each scenario is the measure which was tested in the study (i.e. the gap metering signs). The total length of the scenarios varied between 2900m and 3300m. The latter is used when variable speed limits are tested, due to the necessary spacing. The choice was made to keep the scenarios as short as possible to make sure that the time participants spend in the driving simulator was reasonable.

The scenarios were made up of a straight section of highway. Guidelines state a maximum straight length of 2400m on highways, with a speed of 120km/h, which is shorter than the length used in this study. However, the aim is to test the effect of gap metering systems in an isolated environment. Research suggests that there is a difference in right and left curvatures in the road alignment as they change the point of attention (Mars & Navarro, 2012), and differ in the effect on brain activity due to differences in the required visual attention between right and left turns (Oka et al., 2015). It was not possible to run the study on both right and left turning stretches of highway, and it was, therefore, decided to only make use of a straight stretch of highway.

The traffic is the next important factor for this study. The vehicle directly in front of the participant is the most important vehicle since the study focusses on the gap between the participant and this vehicle. Figure 14 shows the planned location of the simulated through lane traffic. The participant's vehicle is indicated with a red color and the other vehicles with a blue color. Two vehicles were located in front of the driver. These were positioned on the left lane to stop the driver from overtaking and also to stop speeding, hence reducing the chance of collecting incorrect data (for this research purpose). A vehicle was simulated on the left lane behind the participant, in an attempt to persuade participants to stay on the right-hand lane. The choice is made to persuade and not force the participant to stay on the right-hand lane to maintain a level of realism in their behavior and preference of actions.

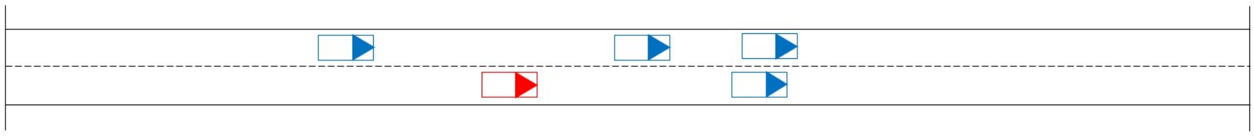

Figure 14 Vehicles simulated in driving simulator study (participant is indicated in red). Source: own material

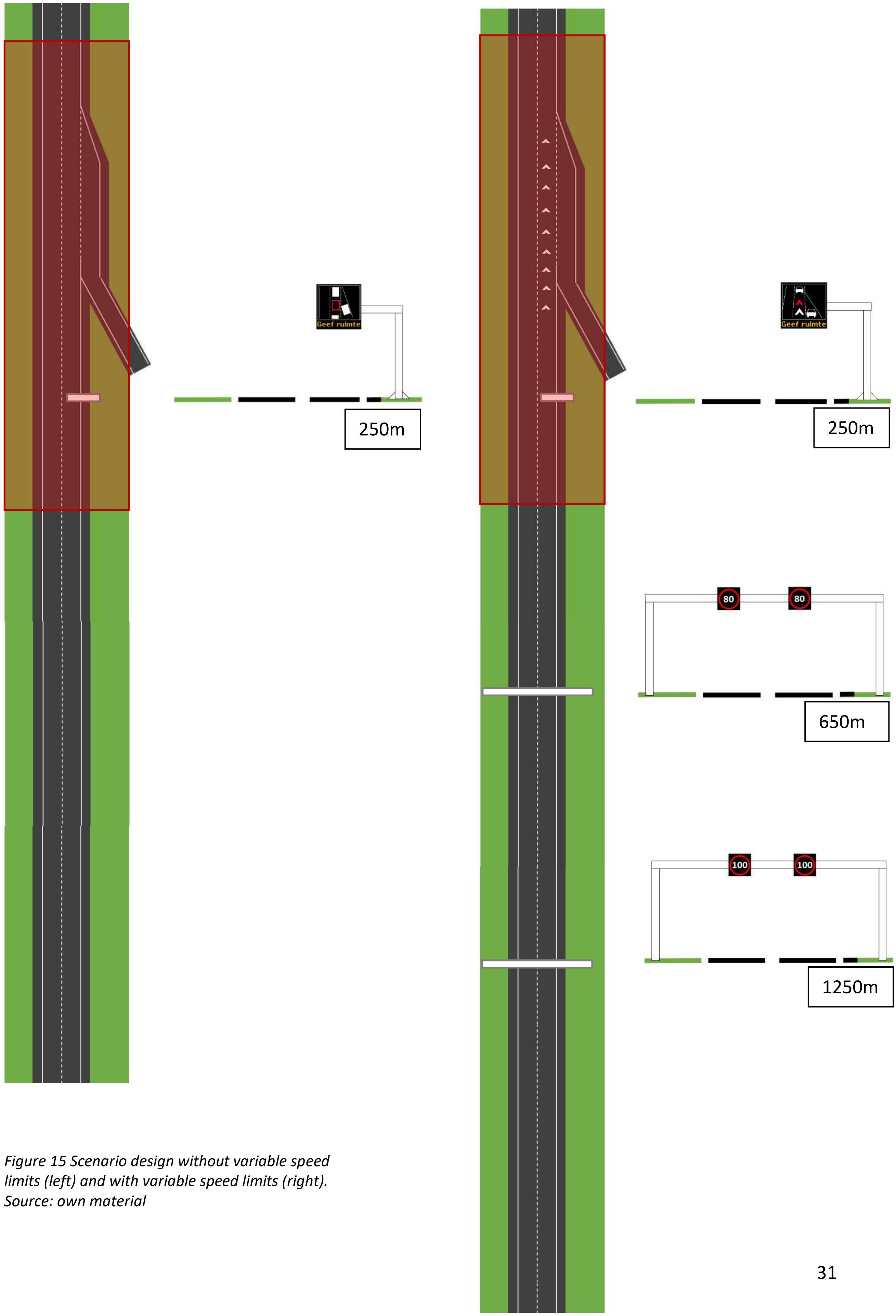

Figure 15 Scenario design without variable speed limits (left) and with variable speed limits (right). Source: own material

5.3. Procedure

Since the study focusses on the effect of gap metering systems in a Flemish context, an important aspect of the study was to exclude participant with no experience of driving on Flemish highways and do not understand the messages shown on the gap metering sign. A recruitment e-mail was sent to everyone at the University of Hasselt to reach out to potential participants. The e-mail explained that the aim of the study was to examine how people drive on highways in general. This information was issued to make participants aware of the environment in which they would drive, without giving away the actual aim of the study. The mail also stated that the study was aimed at Dutch/Flemish speaking people. Having a valid driver's license, and speaking Dutch/Flemish were the only criteria for the selection of participants.

Once participants arrived at the driving simulator, they were asked to fill in a form stating their consent with participating in the research. They also received a short explanation of what would happen with their data and they were assigned an ID number. This number was used for the post-drive questionnaire as well to allow for possible analyses relating the demographic information to the driving simulator data.

Participants received a short explanation of the driving simulator before starting the study, followed by a short practice scenario. This is in line with statements made by Knapper, Christoph, Hagenzieker, and Brookhuis (2015), who state that it is possible that a participant is not familiar with driving in a simulator and/or being monitored and can, therefore, change the driving behavior. Sahami and Sayed (2010) state that if the driving simulator data is collected before the participant adapts to the system, errors and incomplete conclusions can occur. The instructions included information on the vehicle having an automatic gearbox, and on the procedure of what was about to happen. The short practice scenario included different speed limits and an overtaking vehicle to get used to the speed controls of the simulator and the surrounding traffic.

Research by Sahami and Sayed (2010) focused on the adaptation time when driving in curves. The results state an average learning time of 7 minutes. A study by Ronen and Yair (2013) showed that the adaptation time is shorter for straight road driving, compared to curves. There is, however, no exact adaptation time for straight road driving to be found in the literature.

It was therefore chosen to monitor the speed and steering inputs of the participant during the practice scenario to judge if the study could commence. If the participant did not weave out of control, and speeds were close enough to the current speed limit, it was said to be sufficient. Participants were also asked if they felt comfortable with driving in the simulator to judge whether or not to commence.

'Driver simulator sickness' due to the lack of motion is a risk since this can cause participants to drop out (Caird & Horrey, 2011). In order to reduce the risk of participants dropping out, they were given the opportunity to have breaks between scenarios if necessary. The time which participants were exposed to the scenarios was kept also to a minimum to help reduce the risk of participants dropping out. Furthermore, participants received information on the simple symptoms of simulator sickness and were told to indicate when they felt any of these symptoms. The participants were able to terminate their participation at any time during the study.

A total of seven scenarios were presented to the participants, differing in the measure being tested (Table 1). A risk when exposing participants to several, similar, scenarios is the so-called carry-over effect. This happens when the behavior in one scenario is a result of lessons learned in a previous. When all participants drive all scenarios in identical order, it is not possible to state if the difference in outcome is a result of the intervention or of the learning effect.

The scenarios were therefore presented in a predefined randomized order to overcome any possible carry-over effects. Participants were instructed to (relatively) quickly accelerate up to the given speed limits but not exceed it, and to obey traffic laws as they would normally do.

Table 1 *The different test scenarios used during the driving simulator study*

Scenario number	Scenario description
1	Base scenario without any variable message signs
2	Gap metering with a square indication
3	Gap metering with chevron indication (top to bottom)
4	Gap metering with chevron indication (bottom to top)
5	Gap metering with square indication & variable speed limit
6	Gap metering with chevron indication (top to bottom) & variable speed limit
7	Gap metering with chevron indication (bottom to top) & variable speed limit

6. Data collection

Several parameters were logged when a participant drove through a scenario. These parameters included the elapsed time, longitudinal acceleration and velocity, the distance traveled, as well as the lateral lane position, steering wheel angle, and the acceleration due to accelerator and brake pedal input. The data is collected during the simulator study, using a time-based data sampling method with a time increment of 0.014s. This increment corresponds with the frame rate of the IMOB simulator.

After the participant drove all seven scenarios, they were asked to fill in a post-drive questionnaire. The questions were aimed towards the understanding of the task and feelings towards the signs which were presented during the simulator study. The detailed questionnaire, in Dutch, can be found in Appendix A.

The minimal time to collision (TTCmin) and range were collected as well, but while processing the data it became clear that a mistake was made in coding the driving simulator scenarios. This mistake resulted in minimal headway and TTCmin to be calculated for the first vehicle in front, regardless of the lane in which this vehicle was traveling. It is, therefore (nearly) impossible to state whether the values are based on the vehicle in the same lane or another vehicle which just happened to be closer.

Headways where therefore generated based on the known speed of the surrounding vehicles (as defined in the scenario coding) to partly overcome this issue. This process involved generating distance values for a “fictive vehicle” in front of the participant’s vehicle and calculating the difference between this value and the known location of the participant’s vehicle in that moment of time. The headway values for this fictive vehicle are based on the simple rule of “speed x times = distance”. Once headway values were generated it was possible to match the location of the participant to the distance of this fictive vehicle based on the elapsed time in the scenario.

An important issue with this method is that the headways have to be considered an indicative value, and the differences and not the exact values are to be taken as a result. This means that analyses such as “critical headway values” and “lane change based on headway” cannot be conducted using these headway values. Furthermore, the headway is only generated up to the point where the merging vehicle merges onto the highway. The reason for this is that it is not possible to determine whether or not the merging vehicle merges in front of the vehicle in front, or in between both vehicles. Headway values can therefore not be generated with certainty that it is the correct value.

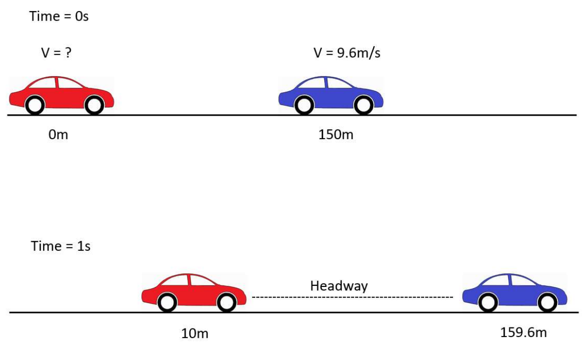

Figure 16 Simple representation of headway generation. Source: own material

Figure 16 shows an example of the procedure as described above. The red vehicle represents the participant. The speed of the participant is not known in this instance. The blue vehicle represents the vehicle in front of the participant. The speed of this vehicle is known from the coding. As stated before, the relationship between both vehicles is determined based on the elapsed time in the scenario.

Since both the ‘distance traveled’ and the ‘elapsed time’ is logged for the participant's vehicle, it is possible to approach the headway using these values. For example, at time 0, the blue vehicle is 150 meters in front of the participant's vehicle. The speed of this vehicle is known, and it is possible to calculate where this vehicle is at time 1. The location of the participant's vehicle is logged, and can thus be retrieved from the data. The difference between both values is the ‘headway distance’.

An extra step was necessary, however, since the analyses use the distance traveled in the scenario and not the elapsed time. This step involved determining the elapsed time based on a given driven distance of the participant's vehicle and comparing this to the time and distance of the fictive vehicle (Figure 17). For example, at 5 meters, the time stamp for the participant can be retrieved from the data. The distance traveled of the fictive vehicle at 5 meters can be approached using this time stamp.

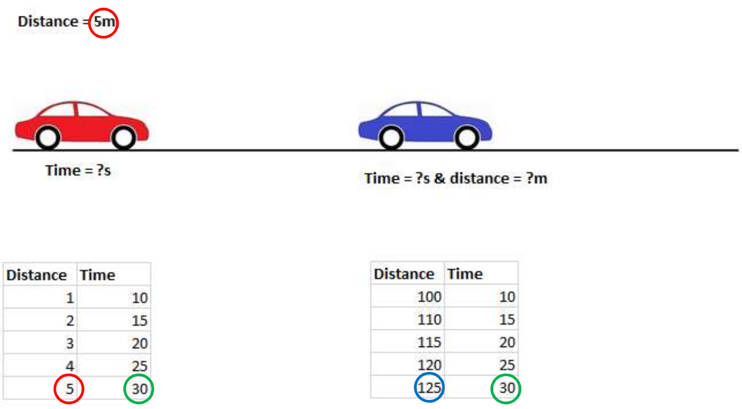

Figure 17 Calculation of headway distance based on distance driven in the scenario

6.1. Data-analysis

A 'zonal analysis' was used to determine where driving behavior changes with respect to the distance driven in the scenario. Since data was collected on a time-based interval, the actual distances were different across all data sets and thus needed to be standardized. Research by Ariën et al. (2015) states the 'nearest value' method might over- or underestimate the parameter values, especially with high driving speeds. Since this research focusses on highway driving, and thus high speeds occur, a 'piecewise linear interpolation technique' as suggested by Ariën et al. (2015) was used to process the raw data before further analysis. Formula 1 shows this technique, where U_b and U_e are the nearest point before and after the point of interest (U) and P_b and P_e are the relevant parameters at U_b and U_e.

$$P_i = P_b + \frac{P_e - P_b}{U_e - U_b} * (U - U_b) \qquad (1)$$

Microsoft Office Excel was used to prepare the raw data for the statistical analyses. A file was created for each participant with the raw data per scenario. The piecewise linear interpolation technique was performed for each of the different parameters, per scenario, with an increment of 5 meters between each step to homogenize the data. Once this was done, the means for each part within the analysis zone was calculated using another formula suggested by Ariën et al. (2015), shown in formula 2. The analysis zone is divided into 11 equal pieces of 50 meters. Figure 18 shows how the analysis zone is split up. The gap metering signs are placed at 0 meters, and the merging vehicle performs this maneuver at 270 meters from the gap metering sign.

$$\overline{P_{DZ}} \cong \frac{\frac{P_0}{2} + P_1 + P_2 \ldots + P_{n-1} + \frac{P_n}{2}}{n} \qquad (2)$$

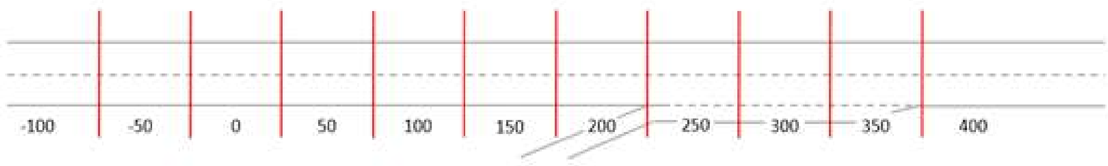

Figure 18 Analysis zone

SPSS was used for the statistical analyses for the different related parameters. All significance levels are set at α = 0.05. The independent variable in these tests are the different strategies and the dependent variables are the speed, lateral position, and the headway distance of the participant.

A 4 (condition) X 11 (zone) within-subject multivariate analyses of variance was used to analysis the mean speed and lateral position for the base scenario and the three scenarios with the different gap metering signs. Additional post hoc univariate tests were conducted for both speed and lateral position if significant effects were found. The scenarios with additional variable speed limits were not taken into account for this analysis since the difference in mean speeds between all seven scenarios is a logical result of the variable speed limits being in place.

The headway to the vehicle in front is not part of the repeated measure analysis due to missing values. These missing values are a result of the fact that headway values are only generated during the data preparation when the participant is driving on the right-hand lane since this is the lane of interest for this study. The difference in headway was tested using an ANOVA and pairwise comparisons for each different scenario. It was not possible to use the paired t-test due to the violation of normality of the data. The same approach is used to test the different effects with regards to the flashing pattern of the chevron signs.

The post-drive questionnaire is only analyzed in a descriptive manner, and the results are used to further understand the outcome of the driving simulator data. Meaning that the stated preference and the comments made by participants are analyzed after the driving simulator data analysis to check for explanatory results when perceived to be necessary.

7. Results

The results of the data analysis are discussed in this chapter. The demographics of the participants are described first. Followed by the analyses and results related to the driving simulator study and the results of the post-drive questionnaire.

7.1. Demographics of the participants

In total 52 people participated in the driving simulator study. 11 cases were excluded for the analysis due to crashes and/or missing data. This choice was made to maintain the strength of the repeated measure analyses. This exclusion left 41 participants with a mean age of 30, where the youngest was 18 and the oldest 67. 25 males (61%) completed the study, and 16 females (39%). The majority of the participants were students, 26 (63%) versus 15 participants (37%) who stated to be working. When asked about driving experience, 6 participants (15%) stated to have their drivers license less than 1 year, 14 participants (34%) stated to have their license between 1 and 5 years, 4 participants (10%) between 5 and 10, and 17 (41%) participants stated to have their license for over 10 years. Participants were asked if they drove as they normally do, 8 participants (20%) stated they did not. The main reason stated for this was that the sensation and controllability of the speed was different to what they are used to. When asked if they found the scenarios which were presented realistic, 19 participants (46%) stated they found it realistic and 8 participants (20%) stated they did not find it realistic. A further 14 participants (34%) answered the question with neutral.

7.2. Driving simulator study

This section elaborates on the results from the driving simulator study. The descriptive results are discussed first in the form of graphs. This is followed by the within-subject multivariate analyses of variance and the post hoc univariate tests, separated into analyses excluding and including the scenarios with variable speed limits. The analyses for the headway are discussed separately. A section on the effect of cruise control habits is added at the end, the idea being that people who normally use their cruise control on the highway might react different to the gap metering system, due to their habits.

7.2.1. Descriptive results

Figure 19 shows the curve of the mean speed in the merging zone, per scenario. The mean speed of the scenarios with variable speed limits (VSL) is lower than that of the other scenarios, as expected. More interesting, however, is the slight difference in speeds between the base scenario and the three scenarios with gap metering in place. The slope of the graph indicates that, for all three of these scenarios, people tend to slow down earlier but end up with relatively similar speeds in the end. This can indicate that people tend to slow down when seeing the gap metering sign, being alerted for the upcoming event of a merging vehicle.

For both forms of gap metering (with and without VSLs) the profile of the mean speed is relatively similar for each design. Meaning that the mean speeds seem similar for each design. The profile of the mean speed for scenarios with VSL in place is smoother compared to the scenarios without VSL. This indicates a more homogeneous traffic flow. This is in line with findings on the effect of VSL on traffic flow in the literature as described before (p.p. 16).

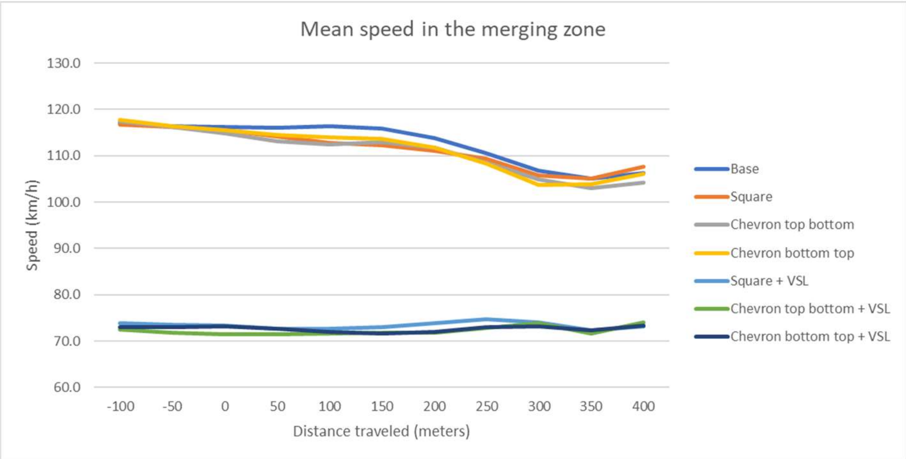

Figure 19 Mean speed in merging zone per scenario

Figure 20 shows the population standard deviation for the speed. The standard deviation is used as a measure of homogeneity of the traffic flow (Zheng, Ahn, & Monsere, 2010). The graph shows that the standard deviations for the base scenario and the three scenarios with gap metering differ only slightly. The standard deviation for the scenarios with VSL is lower, however. This also shows in the slope of the graph in Figure 19. This results further proves that gap metering signs alone do not have a calming effect on the traffic flow.

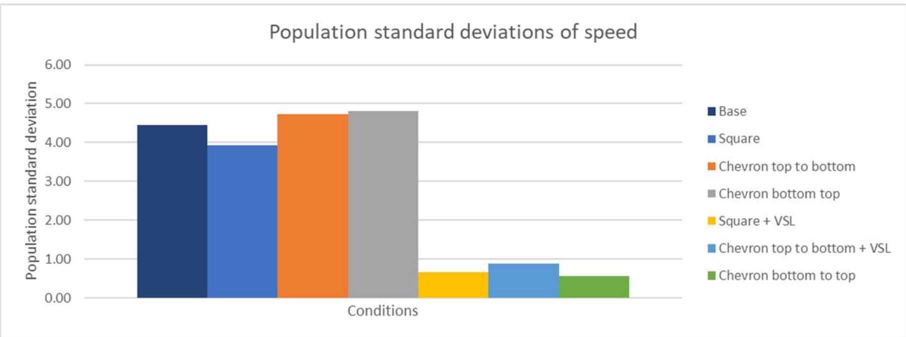

Figure 20 Population standard deviations of speed

Figure 21 shows the mean lateral position of participants in the merging zone. When the value is close to '10' it indicates people driving on the right-hand lane. The lower the value, the more people drive on the left-hand lane of the highway, and thus the more people performed a lane change at that point. To help indicate this, the values on the 'Y axis' are ordered in reverse order.

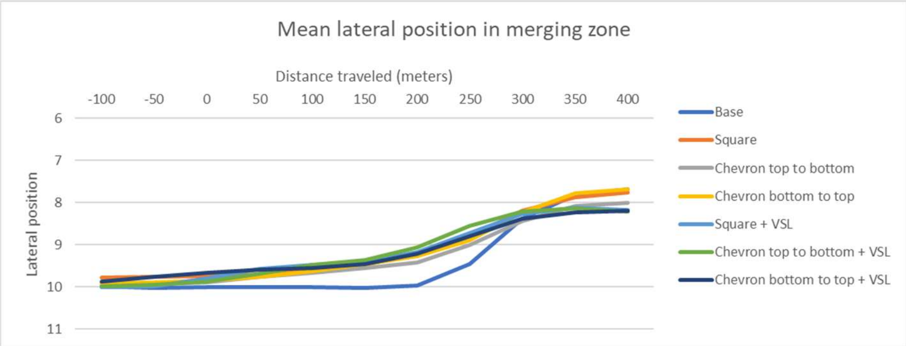

Figure 21 Mean lateral position in the merging zone per scenario

The graph shows that, when no intervention is in place, people change lanes at a later moment compared to when gap metering signs are present. This could indicate that people tend to change lanes earlier due to seeing the gap metering sign and being alerted about the upcoming event. This assumption is in line with the assumption made on the change of mean speeds in the merging zone.

Figure 22 shows the graph of the generated mean headway distances. As stated before, these values are not representative of the true values but were obtained through a number of assumptions and should therefore not be seen as exact values but as an indication. The graph shows that the headway distances tend to be larger for the scenarios which VSLs in place. The headways in these scenarios tend to increase 150 meters after the gap metering sign, to then decrease again. For the scenarios without variable speed limits, there is a decrease in headway distances shortly after the gap metering sign, between 50 meters and 100 meters after the gap metering sign. This is followed by an increase in headway just before the moment the merging vehicle joins the through lane of the highway. The profiles for the scenarios without variable speed limits in place are relatively similar to each other.

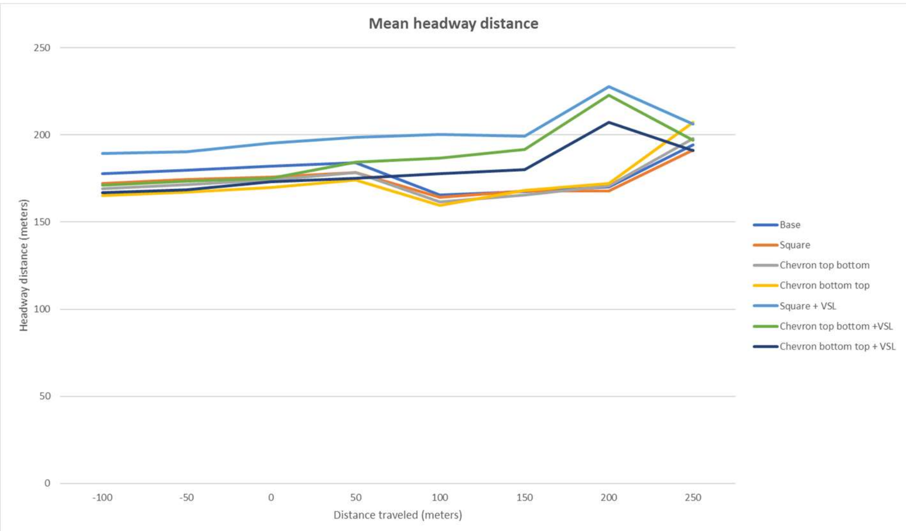

Figure 22 Mean headway distances in the merging zone per scenario

7.2.2. Test of within-subjects effects without for gap metering systems without variable speed limits

The results of the repeated measures multivariate test (Table 2) show a significant main effects for the zone ($F_{20,798}$ = 90,917; p < 0,05) and the condition ($F_{6,238}$ = 2,750; p < 0,05) when both the mean speed and the lateral position are taken into account. Furthermore, the table shows a significant interaction between the zone and the condition ($F_{60,2396}$ = 1,731; p < 0,05). An univariate test is applied to understand the individual effects for the mean speed and the lateral position.

Table 2 *Multivariate test results for mean speed and lateral position not including scenarios with variable speed limits*

	Wilks' Lambda	F (df)	Sig.	Partial eta squared
Zone	0,093	$90{,}917_{20,798}$	0,000*	0,695
Condition	0,875	$2{,}750_{6,238}$	0,013*	0,065
Zone*condition	0,919	$1{,}731_{60,2396}$	0,002*	0,042

**significant at α<0,05*

Table 3 *Univariate test results (Greenhouse-Geisser) for mean speed and lateral position not including scenarios with variable speed limits*

Mean speed	F (df)	Sig.	Partial eta squared
Zone	$50{,}197_{1,841}$	0,000*	0,557
Condition	$1{,}433_{2,620}$	0,240	0,035
Zone * Condition	$0{,}886_{4,857}$	0,489	0,022
Lateral position			
Zone	$111{,}776_{1,620}$	0,000*	0,736
Condition	$2{,}003_{2,525}$	0,128	0,048
Zone * Condition	$1{,}847_{5,423}$	0,128	0,044

**significant at α<0,05*

The repeated measures univariate test results (Table 3) shows that, when the mean speed and lateral position are viewed independently, there is only a significant main effect for the zone for both the mean speed ($F_{1,841}$ = 50,197; p < 0,05) and the lateral position ($F_{1,620}$ = 111,776; p < 0,05). Since there is no significant effect of the different conditions, nor an interaction, the result indicates that people change their driving behavior due to the distance they drove in the merging zone. This change has most likely to do with their normal behavior when seeing the on-ramp or seeing the merging vehicle. This was however not questioned during the post-drive questionnaire and is therefore only an assumption.

As stated before, the headway results cannot be analyzed using the repeated measures models. An ANOVA is therefore used to analyze the differences in mean headway distances between scenarios. Once again, the scenarios with a VSL in place are excluded from this analysis.

***Table 4** Results of the ANOVA for the headway of scenarios without variable speed limits*

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	153731,335	6	25621,889	6,089	0,000*
Within Groups	9821682,603	2334	4208,090		
Total	9975413,938	2340			

Headway	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1232,818	2	616,409	0,171	0,843
Within Groups	3597836,683	997	3608,663		
Total	3599069,501	999			

Table 4 shows the results of the ANOVA for the headway distances of the scenarios without VSL in place. The results show no significant difference in mean headway distances between the four different scenarios ($F_{2,997}$ = 0.171; p > 0.05). This indicates that there is no effect of the gap metering signs on the mean headway distances kept by drivers.

7.2.3. Test of within-subjects effects for gap metering systems including variable speed limits

Lateral position	F (df)	Sig.	Partial eta squared
Zone	$110{,}757_{1{,}796}$	0,000*	0,740
Condition	$1{,}156_{4{,}305}$	0,333	0,029
Zone*condition	$2{,}372_{9{,}486}$	0,011	0,057

Table 5 shows the results of a repeated measures ANOVA for the lateral position for all seven scenarios. Fout! **Ongeldige bladwijzerverwijzing.** shows the results of an ANOVA for the headway, including all scenarios. The results show a significant difference between the mean headways when all seven scenarios are taken into account ($F_{6,2334}$ = 6,089; p < 0,05). This indicates a difference in headways between at least two of the different scenarios.

Table 6 shows the result of an ANOVA of the headway for all seven scenarios. The mean speed is not taken into account when testing the effect of variable speed limits in relation to gap metering as stated before.

***Table 5** Repeated measures test within-subject results (Greenhouse-Geisser) for the lateral position for all scenarios* *significant at α<0,05*

Table 5 shows the repeated measures test within-subject results for the lateral position for all seven scenarios. The results indicate no significant main effect for the condition ($F_{4,305}$ = 1,156; p > 0,05). There is a significant main effect for the zone ($F_{1,796}$ = 110,575; p < 0,05) and a significant interaction effect between the zone and the condition ($F_{9,486}$ = 2,372; p < 0,05).

Fout! Ongeldige bladwijzerverwijzing. shows the results of an ANOVA for the headway, including all scenarios. The results show a significant difference between the mean headways when all seven scenarios are taken into account ($F_{6,2334}$ = 6,089; p < 0,05). This indicates a difference in headways between at least two of the different scenarios.

***Table 6** Results of the ANOVA for the headway of all scenarios*

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	153731,335	6	25621,889	6,089	0,000*
Within Groups	9821682,603	2334	4208,090		
Total	9975413,938	2340			

**significant at α<0.05*

A Bonferroni pairwise comparison shows that the difference occurs for the scenario where a square design is used for the gap metering, with a VSL in place. Table 7 shows the comparison between the base scenario and all other scenarios. The complete table of the results of the multiple comparison analysis can be found in Appendix B. This result is however rather isolated since the mean headway distance does not change in any of the other scenarios with VSLs nor with the same gap metering sign. Furthermore, as stated before, the headway values cannot be used as exact values, but as an indication. Caution should thus be taken when formulating a conclusion for the mean difference of the means headways.

***Table 7** Bonferroni pairwise comparison for the mean headway distances*

(I) Condition	(J) Condition	Mean Difference (I-J)	Sig.
Base	Square	2,45067	1,000
	Chevron top bottom	3,29967	1,000
	Chevron bottom top	0,63990	1,000
	Square + VSL	-21,68623	0,000*
	Chevron top bottom + VSL	-6,32953	1,000
	Chevron bottom top + VSL	0,43679	1,000

**significant at α<0.05*

7.2.4. Pairwise comparison of mean speeds and mean lateral position per scenario

The previous analyses show that the only significant difference between mean speed and mean lateral position occurs as a result of the distance driven in the analysis zone. Two pairwise analyses are therefore used to further understand the effect of gap metering sings on the mean speed and mean lateral position of the participants. The detailed analyses can be found in Appendix C and Appendix D. Each analysis is divided into the eleven measurement zones to understand where the behavior changes. Each analysis is performed for each individual scenario, meaning that the changes are compared to the previous zone in that scenario and not between scenarios for that zone. In short, the comparison is made for example “zone 2 vs zone 1 for scenario 1” and not “scenario 2 vs scenario 1 for zone 1”.

The gap metering signs are placed at 0m, the on-ramp became clearly visible around 180m for participants, and the merging vehicle entered the highway around 250m. The 'X' marks a zone where there is a significant difference in mean speed compared to the previous zone. The scenario numbering corresponds with the numbering in Table 1, with 1 being the base scenario, 2 the scenario with a square design, 3 the scenario with chevron indication (top to bottom), and 4 being the scenario with Gap metering with chevron indication (bottom to top). Scenario 5, 6, and 7 use the same order of the different designs, the difference is the addition of the variable speed limits in these scenarios.

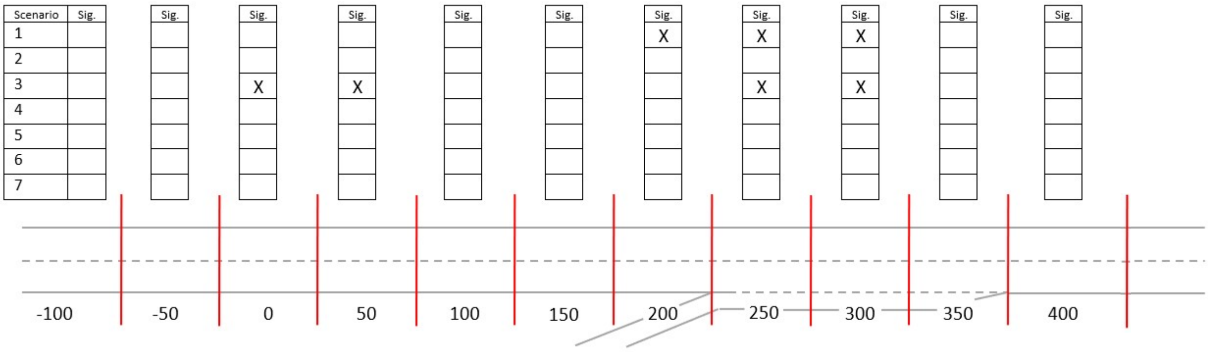

Figure 23 Pairwise comparison between zones for the mean speed

The results of the pairwise analysis of the mean speed per zone are graphically represented in Figure 23. The zones in which the speed changes significantly compared to the previous zone are indicated with an 'X'. When this happens, it shows a sudden change in driving speeds. This can indicate a situation in which a driver has to suddenly react to the merging vehicle for example. The figure shows that in the base scenario, without gap metering signs, this phenomenon occurs in the zones where the merging zone becomes visible, and where the merging vehicle enters the highway. The latter is also true for the scenario with chevron markings flashing from top to bottom. All other scenarios show no significant differences in speed. This means that there are no sudden changes in speed in these scenarios. This result is in line with the general results of the mean speeds, where the graph (Figure 19) indicates that, when gap metering signs are present, people tend to slow down earlier but end up at a similar speed. This means that the process of slowing down is less abrupt.

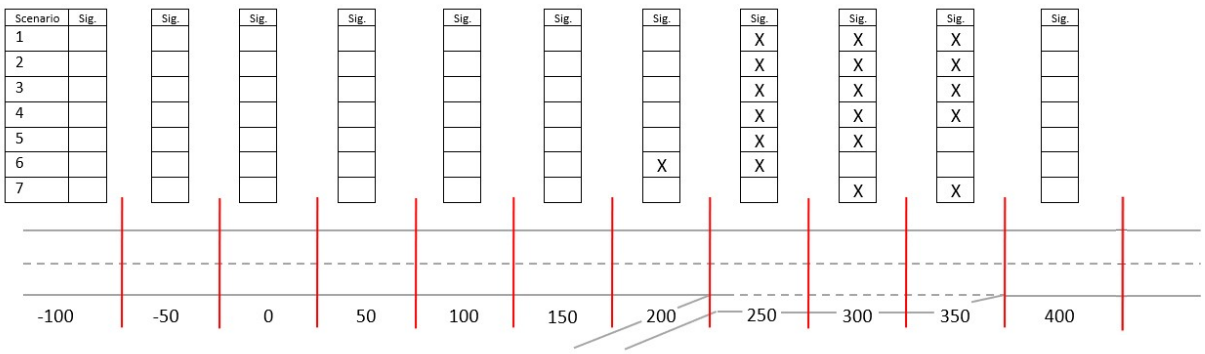

Figure 24 Pairwise comparison of zones for the lateral position

The results of the pairwise analysis of the lateral position per zone are graphically represented in Figure 24. The zones in which the lateral position changes significantly compared to the previous zone are indicated with an 'X'. This happens when a significant amount of people change from the right-hand lane to the left-hand lane. The results of the pairwise comparison clearly show that the moment where most people tend to change lanes is relatively similar for all scenarios. This is especially true for the scenarios without VSLs. The trend does not show when VSLs are in place. The moment where a significant amount of people made a lane change differs per scenario in this case. Based on this finding it is, however, possible to state that the gap metering signs do not influence people's choice to change lane, but that this decision is based on noticing the presence of a merging vehicle or spotting the on-ramp.

7.2.1. The impact of cruise control habits

The driving simulator did not provide cruise control. It is, however, of interest to see if people who are used to using cruise control have a different reaction to the people who do not use cruise control on a regular basis. A question was therefore added into the post-drive questionnaire to find out whether or not someone uses cruise control. 19 (46%) participants stated to never use cruise control, and 22 (54%) participants stated to either always use cruise control or use it on a regular basis when driving on the highway. The hypothesis behind this extra analysis is that people who are used to driving with cruise control react different to the gap metering signs, compared to people who are used to drive without a form of speed assistance.

Table 8 *Multivariate test results for mean speed and lateral position not including scenarios with variable speed limits with cruise control habits*

	Wilks' Lambda	F (df)	Sig.	Partial eta squared
Zone * Cruise control	0,907	$1{,}938_{20,778}$	0,008*	0,047
Condition * Cruise control	0,956	$0{,}879_{6,232}$	0,511	0,022
Zone*Condition* Cruise control	0,943	$1{,}157_{60,2338}$	0,194	0,029

**significant at α<0,05*

A repeated measures multivariate test is used to test both mean speed and lateral position, with cruise control as a between-subjects factor. The results, Table 8, show that when cruise control usage is added as a between-subject factor, the only significant interaction occurs with the mean speed and mean lateral position for the zones ($F_{20,778}$ = 1,938; p < 0,05). This is in line with the previous findings, and it also indicates that the habit of using a cruise control does not affect the mean speed or lateral position between the base scenario and the scenarios with gap metering when no cruise control is present. Univariate tests show no significant effect for either mean speed or the lateral position (Table 9).

Table 9 *Univariate test results (Greenhouse-Geisser) for mean speed and lateral position not including scenarios with variable speed limits with cruise control habits*

Mean speed	F (df)	Sig.	Partial eta squared
Zone * Cruise control	$1{,}114_{1,866}$	0,331	0,028
Condition * Cruise control	$1{,}128_{2,606}$	0,337	0,028
Zone*Condition*Cruise control	$1{,}633_{4,707}$	0,157	0,040
Lateral position			
Zone * Cruise control	$1{,}235_{1,548}$	0,290	0,031
Condition * Cruise control	$0{,}606_{2,498}$	0,583	0,015
Zone*Condition*Cruise control	$0{,}615_{5,349}$	0,700	0,016

A separate repeated measures ANOVA for the lateral position which includes all seven scenarios is conducted to further analyze the effect of cruise control habits on the effect of gap metering. The results of this analysis are shown in Table 10. Just as with the scenarios excluding the VSLs, no significant effects are found when cruise control habits are used as a between-subjects factor.

Table 10 *Repeated measures test within-subject results (Greenhouse-Geisser) for the lateral position for all scenarios with cruise control habits*

Lateral position	F (df)	Sig.	Partial eta squared
Zone * Cruise control	$2{,}192_{1{,}684}$	0,128	0,053
Condition * Cruise control	$1{,}521_{4{,}194}$	0,196	0,038
Zone*Condition*Cruise control	$0{,}848_{9{,}114}$	0,574	0,021

A three-way ANOVA for the mean headway distances for all scenarios is conducted to analyze the effect of cruise control habits. The analysis included the analysis zones, the analysis conditions, and the cruise control habits. The results are shown in Table 11. The three-way ANOVA indicates a significant interaction between the condition and the cruise control habits ($F_{12,2110}$ = 3,652; p < 0,05) for the mean headway distances.

Table 11 *Results of the three-way ANOVA for the headway of all scenarios with cruise control habits*

Source	Sum of squares	df	Mean Square	F	Sig.
Cruise control * Condition	170081,084	12	14173,424	3.652	0,000*
Cruise control * Zone	51642,998	20	2582,150	0.665	0,863
Cruise control * Condition * Zone	128772,054	120	1073,100	0.277	1,000
Error	8188086,391	2110	3880,610		

**significant at α<0,05*

Based on the results of the three-way ANOVA for the mean headway distances a simple effect multiple comparison test for the interaction between cruise control habits and conditions is made (Table 12). The analysis focusses on the non-use of cruise control versus the use of cruise control.

Table 12 *Simple effect multiple comparison test for the interaction between cruise control habits and conditions*

Scenario	(I) Cruise control	(J) Cruise control	Mean Difference (I-J)	Significance
1	No	Yes sometimes	4,961	0,572
		Yes always	23,568	0,014*
2	No	Yes sometimes	24,277	0,005*
		Yes always	54,889	0,000*
3	No	Yes sometimes	2,997	0,722
		Yes always	42,165	0,000*
4	No	Yes sometimes	2,322	0,788
		Yes always	7,881	0,452
5	No	Yes sometimes	-6,249	0,458
		Yes always	10,942	0,231
6	No	Yes sometimes	22,593	0,011*
		Yes always	52,634	0,000*
7	No	Yes sometimes	45,021	0,000*
		Yes always	55,350	0,000*

**significant at $\alpha<0.05$*

The analysis shows significant increases in the mean headway distances for several conditions for people who stated to use their cruise control versus non-users. There is however no clear trend visible in the results. It can, therefore, be concluded that the gap metering signs do not have a real effect on the mean headways when addressing cruise control habits.

7.2.2. Conclusion

The analyses focused on the mean speed, the mean lateral position, and the mean headways. These parameters were chosen based on the research questions which have to be answered based on these results. The different analyses are split up based on the inclusion of the scenarios with variable speed limits. This choice was made since it was known beforehand that the mean speeds will differ significantly as a result of the variable speed limits.

A general overview of the graphs presenting the profiles of both the mean speed and the mean lateral position revealed that the mean speeds are in fact substantially lower for the scenarios with variable speed limits. The curve of the mean speed shows that when gap metering signs are in place, the speeds start to decline earlier but the end speeds are relatively similar. The curve for the mean lateral position indicated that people changed from the right-hand lane to the left-hand lane earlier when the gap metering signs were in place. This indicates that people possibly change their driving behavior based on detection of the gap metering sign, and adapt their behavior based on the awareness of the upcoming situation.

The analyses excluding the variable speed limits show no significant main effect of the condition (i.e. the different scenarios) on the mean speed, the mean lateral position, or the mean headway distances. Univariate tests for the mean speed and the mean lateral position revealed that there was an effect of the analysis zone on both parameters. This result indicates that people change their speed and lateral position based on the distance driven, and thus on seeing the merging vehicle or the seeing the on-ramp. Pairwise comparisons of the zones showed that this is a plausible assumption.

When the scenarios with variable speed limits are included in the analysis, a similar trend is visible for the mean lateral position. However, there is a significant effect of the condition on the mean headway when variable speed limits are included. A post-hoc analysis showed that this difference only occurs when the gap metering sign with a square design is used in combination with variable speed limits. It is therefore difficult to state if this is an effect of the combination of both measures, since the other two scenarios do not show this effect, nor does the square design on its own show this result.

The impact of cruise control habits is also analyzed, based on the assumption that it has an effect on the driving style of people. The analysis showed no effect on the mean speeds or mean lateral position for both scenarios with and without variable speed limits in place. There is a significant effect of the different conditions on the mean headway distances of drivers with regards to cruise control habits. A pairwise analysis revealed that there are significant increases in the mean headway distances when people either use their cruise control on highways on a regular basis or use if all the time. There is however no clear, or relevant trend visible in these results.

7.3. Post-drive questionnaire

As stated before, participants were asked to fill in a post-drive questionnaire after finishing the driving simulator study. The participants were questioned on their understanding and preference of the different signs. Questions to try to determine attitudes towards gap metering as an intervention to increase the safety in merging zones were part of the questionnaire as well.

7.3.1. Understanding of the gap metering signs

Figure 25 shows the frequencies of the stated level of understanding. The graph clearly indicates that both design types are considered to be either clear or very clear. Only a small proportion stated to find the signs unclear, and no one stated to find any of the signs very unclear.

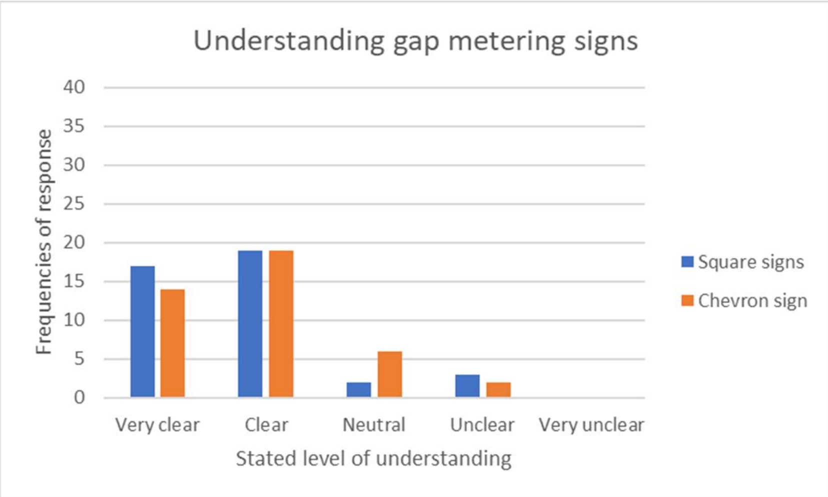

Figure 25 Understanding of gap metering signs

Participants stated that for the design with a square, the graphical image was clear to understand. The less detailed image did not form a problem for people to understand. Several people stated that the textual message helped them to understand what the desired behavior was in the situation. For the chevron design, participants stated that they found it clear due to the detailed image and the indication of which distance to keep. Participants stated that this was both due to the number of chevrons shown on the sign, and the chevrons shown on the road surface.

The people who answered that the square design was not clear, but that the chevron design is clear stated that this was due to the detailed design. They stated that the “blocks” were not clear, whereas the more detailed chevron signs gave a better indication of what was about to happen and what they needed to do. The people who said that the chevron design was not clear, but the square design was clear to them stated that this has to do with the chevrons giving them the idea they had to speed up, or that they were not allowed to drive in that lane. No one stated that both signs were unclear to them.

7.3.2. Preference for designs of gap metering signs

Figure 26 shows the stated preference for the design of the gap metering sign. Participants were asked to make a choice between the design using a square, and the chevrons. The table shows that there is no preference towards one design. 1 participant failed to answer this question.

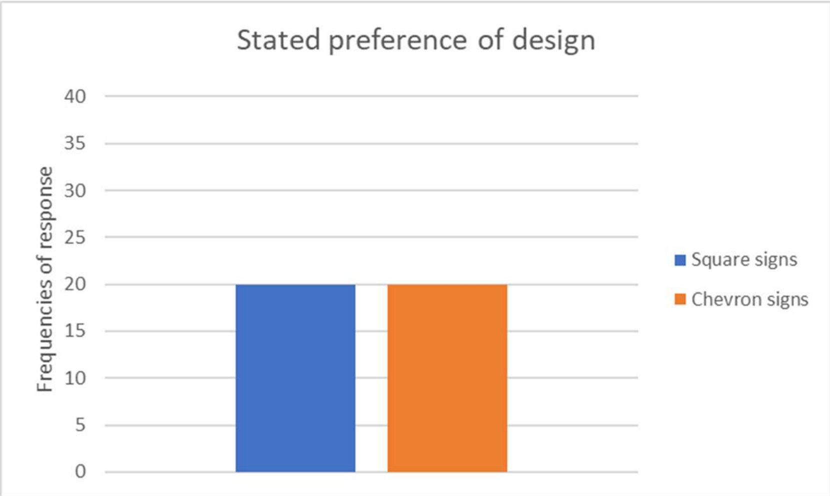

Figure 26 Stated preference of design

Participants were asked to explain their reasoning. The main reason stated for the preference of the square design is that the chevron marking works confusing. People stated they thought the signs were meant to indicate the necessity to speed up and confusion due to a recollection from other uses of chevron markings, such as in weather conditions with minimal sight distances. The main stated reason for the preference of chevron marking was that the design and perspective of the sign was easier to understand and felt like a more realistic representation of the scenario.

The difference in flashing patterns

As stated before, two versions of the chevron pattern signs were tested in the driving simulator study. One version showed chevrons flashing from the top to the bottom and one version showed chevrons flashing from the bottom to the top. Participants were asked if they noticed the difference between both flashing patterns. 4 participants (10%) stated they noticed the difference, the majority of participants, 37 in total (90%), stated they did not notice the difference, however.

7.3.3. Attitudes towards gap metering

The effectiveness of a certain system strongly depends on drivers finding it acceptable (i.e. seeing a need for the system) (Regan, Horberry, & Stevens, 2014). Furthermore, Najm, Stearns, Howarth, Koopmann, and Hitz (2006) claim that the driver's acceptance is the precondition for new transport technologies to reach their desired and predicted benefits.

Six questions, making use of a 5 point Likert-scale ranging from strongly agree to strongly disagree, were used to question the general attitudes towards gap metering as a system to increase the safety in merging zones. These questions are as following:

Q1 I regularly experience a feeling of not having enough space to merge in a safe manner;

Q2 A solution such as gap metering has an added value with regards to traffic safety in my opinion;

Q3 I find the message/instructions of the gap metering signs as clear;

Q4 A solution such as gap metering will be too distracting during driving in my opinion;

Q5 When faced with gap metering signs I will follow the instructions presented to me;

Q6 Gap metering signs make me aware of the fact that a vehicle is about to merge onto the highway in my opinion.

Table 13 *Frequencies of answers to the questions, in percentages*

Questions	n	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1	41	2%	32%	24%	32%	10%
Q2	41	0%	2%	5%	63%	29%
Q3	41	0%	7%	15%	51%	27%
Q4	41	12%	71%	10%	7%	0%
Q5	41	0%	2%	15%	66%	17%
Q6	41	0%	2%	12%	44%	41%

The results of the questions are shown in Table 13, the frequencies of the responses are shown in percentages. The table shows that a majority of people state to experience situations where they feel that they do not have enough room to safely merge into traffic on a regular basis. When asked if they feel that gap metering has a positive effect on traffic safety, the majority of people questioned state they do see a benefit for traffic safety.

As became clear in previous questions, the majority of people state that the messages on gap metering signs are clear. When asked whether or not the gap metering signs would form a distraction for them whilst driving, a majority stated they do not feel like this. A majority also stated they would follow the instructions presented to them on gap metering signs when driving on the highway.

Gap metering signs can alert drivers of the upcoming situations. When question whether or not the gap metering signs create an awareness of the fact that a vehicle is about to merge onto the highway a majority stated that they agree to this. This raised awareness can explain why mean speeds started to decrease earlier, and why the lane changes are made earlier when gap metering signs are in place.

Based on these results it is possible to state that participants are faced with situations in which gap metering potentially provides a solution on a regular basis, and they feel that such a system can have a positive effect on traffic safety in merging zones. They state that gap metering signs do not form a distraction while driving, in contrast, they create awareness for the upcoming situation.

7.3.4. Conclusion

The majority of the participants stated to find both signs clear, and when questioned about their preference the result was split. The less detailed image used for the square design did not form a problem for people to understand. The detailed image used for the chevron design did make it easier to understand how much space one should leave according to the results, this was also due to the chevrons on the road surface according to the stated answers of the participants. Several people stated that the textual message helped them to understand what the desired behavior was in the situation. The difference in the flashing pattern was not noticed by 90% of the participants.

Those who stated they found the square sign unclear, but the chevron sign clear, said this was due to the "blocks" not being clear. The more detailed sign gave a better indication of the situation up ahead. The people who said that the chevron design was not clear, but the square design was clear to them stated that this has to do with the chevrons giving them the idea they had to speed up, or that they were not allowed to drive in that lane. No one stated that both signs were unclear to them.

When addressing the acceptance of gap metering as a system to increase the safety in the merging zone, the majority of the people state to find themselves in relevant situations on a regular basis. The signs are not seen as a distraction by the participants, and most stated to be willing to adhere to the instructions given on by the gap metering sign. The participants also stated that the sign raised their awareness of the upcoming situation, i.e. making it clear that another vehicle was about to merge into their lane.

8. Discussion

The results presented in this document show that gap metering has no significant effect on the headway distances, the mean speed, or the location and amount of lane changes. An interesting finding is that people tend to change speeds earlier when gap metering signs are in place. This can indicate that people lower their speed due to the awareness of the upcoming scenario. The reduction in speed can be an effect of drivers scanning for clues in their surroundings based on the message provided by the gap metering sign. Similar behavior was also found in a study on the effect of variable message signs on slippery road conditions (Rämä & Kulmala, 2000). Participants stated to find that the gap metering signs raised their awareness of the upcoming situation.

Another interesting finding is that people tend to change lanes in similar locations when gap metering signs are present as for the base scenario with no measures in place. This is in line with previous findings which state that drivers prefer to change lanes to allow a merging vehicle to enter the highway, compared to changing their own speed to create a gap. (Kondyli & Elefteriadou 2009) (Kondyli & Elefteriadou 2012). The results reveal that the gap metering sign alone does not persuade people to choose to reduce speed and leave a gap over changing from lane to create a sufficient gap. Hence, the gap metering signs do not help to mitigate the problems caused by oscillations in the traffic flow as a result of the so-called, courtesy yield.

The design of the sign does not show any significant effect in both the driving simulator data and the stated preference and understanding by the participants. The hypothesis made at the start of this study stating that "chevron markings are easier to understand for road users and result in larger headways, due to the indication of distance" is therefore not supported by the findings of this study. There is no significant difference in the mean headway distance between the two different designs. Furthermore, the post-drive questionnaire revealed that there is no strong preference for a certain design, nor is there a substantial difference in the understanding of the sign

The second hypothesis made at the beginning of this study related to the potential benefits of variable speed limits. The hypothesis stated that "the use of variable speed limits has a positive effect on gap metering systems". Variable speed limits do have a calming effect on oscillations in the flow of traffic. This is, however, a known effect of variable speed limits and can therefore not be seen as a result with regards to this study. (Carlson, Papamichail, Papageorgiou, & Messmer 2010) (van Nes, Brandenburg, & Twisk, 2010) (Highways Agency, 2004). There is however no stable significant difference in mean headway distances or mean lateral positions. Significant results are inconclusive, as they are isolated and show no trend. This indicates that there is no benefit of variable speed limits in addition to a smoother flow of traffic. There is, therefore, no evidence to support the hypothesis as stated before.

The third hypothesis stated that "chevron markings flashing against the flow of traffic result in lower speeds and larger headways". Neither the driving simulator data nor the results from the post-drive questionnaire support this hypothesis. There is no significant difference in the mean headway distance between the two different patterns. Furthermore, the post-drive questionnaire revealed that the difference was not noticeable for the participants during the driving simulator study. An explanation for the latter can be found in the 'Paillard-Fraisse hypothesis' which states that the experience of directional movement is dependent on the order in which stimuli are processed (Arstila, 2016). This means that, when stimulus A is processed before stimulus B, the person experiences this as the direction of movement.

In the case of the chevrons, it means that the perception of different directions is dependent on which chevron one saw flashing first. If this was the top one in all cases, the participant will only process a movement from the top to bottom, and not the other direction even though this pattern is present. No literature was found on whether or not a third chevron would have a positive effect on the perception of movement of the flashing pattern.

9. Limitations and future research

There are however some shortcomings and limitations in this research which have to be addressed when assessing these results. First and foremost, the mean headway values. These were not collected during the simulator study but generated afterwards based on some assumptions. This means that they cannot be seen as true values, but have to be seen as an indication, and the relative changes have to be seen as the actual result. This in turn meant that is wasn't possible to perform analyses based on a critical gap between the participant and the vehicle in front at the time of merging. Since this moment cannot be calculated with a hundred percent certainty.

Another consequence of the coding mistake which resulted in wrong headway values is that the minimal time to collision (TTCmin) was also calculated in the same manner in STISIM. Resulting in those values being useless with regards to this analysis. It is possible to calculate the TTCmin for non-perpendicular interactions. For an explanation of these calculations see appendix A of Laureshyn, Svensson, and Hydén (2010). However, due to the time constraints of this research, the choice was made to not make these calculations.

A limitation of this research is the lack of a control scenario with variable speed limits. The scenarios with variable speed limits in addition to gap metering could not be compared to a scenario with variable speed limits without gap metering in place. As a result, it is harder to state whether the differences between scenarios with and without variable speed limits are solely due to the variable speed limit, or if the gap metering does play a role. This is relevant for the practical use of a system such as gap metering, as it is important to understand if it is necessary to have variable speed limits in place as well.

Another limitation is the fact that people could move over. This is due to the decision to allow people to move over. The choice was made to not force people to stay in the right-hand lane to maintain a level of realism. It does, however, show that if people can still move over, they are likely to do so. This resulted in a loss of data since people left the lane of interest before they reached the crucial point of interest for this study, the moment the merging vehicle enters the highway.

These shortcomings promote interesting chances for future research. It is, for example, interesting to study what the effect of gap metering is when drivers are forced to stay on the right lane by means of continuous markings. It is possible that gap metering signs do result in larger headways and lower speeds in those cases. It is also important to develop a threshold value at which gap metering systems can be put in use in real-world scenarios.

10. Final conclusion & recommendations

Several possible measures to increase the safety of merging zones are discussed in this document. Gap metering is the only one strategy which actively create gaps in the through lane traffic. Gap metering systems involve a sign stating that a driver has to leave space for a merging driver, accompanied by a graphical image to indicate said behavior. This measure is considered to be best suited to help mitigate the safety issues in merging zones since it is aimed at the core issue, the lack of gaps in the traffic.

Results of this study show that there is no conclusive effects on the relevant parameters when gap metering is in place, compared to the base scenario without any measure in place. Further analyses showed that the change in speed was less abrupt when gap metering was in place. This indicates that the gap metering sign has a smoothing effect on the flow of traffic in merging zones. However, the speed of the participants at the time which the merging vehicle performed the maneuver was not different to that in the base scenario at the same location. The results also show that people tend perform a lane change at similar locations when gap metering signs are in place, compared to the base scenario. This indicates that gap metering does not help to reduce the oscillations in the flow of traffic as a result of lane changing, and thus does not help to reduce the risk of accidents due to this sudden increase of density in the traffic flow.

With regards to the three research questions. The data shows that there is no difference in the actual design of the gap metering sign (i.e. square versus chevron marking). This is proved by both the data from the driving simulator as the stated preference and understanding of the participants during the post-drive questionnaire. The addition of variable speed limits also showed no conclusive effect on the mean headways, nor lateral position, of the drivers. The pattern in which the chevron marking flashed was not noticed by a large majority of the participants. The driving simulator data also suggest that there is no subconscious effect of the flashing pattern, as speed values did not differ from each other.

One has to be cautious when making practical recommendations based on the results of this study for the use of gap metering systems on highways, as the results are inconclusive. The post-drive questionnaire revealed that people find the signs useful, and they are not perceived as a distraction when driving on the highway. In contrast, people stated that the sign helped them to be aware of an upcoming merging vehicle. The results also show that there is no clear “better” design for the sign itself. However, since the exact headway values are missing it is hard to state whether or not the headway is affected by the gap metering sign. This is important to know, as this is a crucial reasoning to implement gap metering systems.

Sources

Agentschap Wegen en Verkeer. (2014). *Deel III: wegmarkeringen*. Retrieved from https://wegenenverkeer.be/sites/awv/files/docs/MOW-AWV-2014-12bijlage1.pdf

Ariën, C., Brijs, K., Jongen, E. M. M., Vanroelen, G., Cornu, J., Daniels, S., … Wets, G. (2015). Processing driving simulator data before statistical analysis by means of interpolation and a simple integral formula. *Proceedings of the 2015 Road Safety & Simulation International Conference, Essam Radwan, Orlando, United States*, 756–769.

Arstila, V. (2016). Theories of apparent motion. *Phenomenology and the Cognitive Sciences*, *15*(3), 337–358. https://doi.org/10.1007/s11097-015-9418-y

Ben-Bassat, T., & Shinar, D. (2006). Ergonomic Guidelines for Traffic Sign Design Increase Sign Comprehension. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *48*(1), 182–195. https://doi.org/10.1518/001872006776412298

Bianchi Piccinini, G. F., Rodrigues, C. M., Leitão, M., & Simões, A. (2014). Driver’s behavioral adaptation to Adaptive Cruise Control (ACC): The case of speed and time headway. *Journal of Safety Research*, *49*, 77.e1-84. https://doi.org/10.1016/j.jsr.2014.02.010

British Columbia. Ministry of Transportation and Highways. (2000). *manual of standard traffic signs & pavement markings*.

Caird, J. K., & Horrey, W. J. (2011). Twelve Pratical and Useful Questions About Driving Simulation.

Calvi, A., & De Blasiis, M. R. (2011). Driver Behavior on Acceleration Lanes: Driving Simulator Study. *Transportation Research Record: Journal of the Transportation Research Board*, *2248*(1), 96–103. https://doi.org/10.3141/2248-13

Cambridge Systematics, Inc. (2001). Twin Cities Ramp Meter Evaluation - Final Report. *Final Report*, 10.

Carlson, R. C., Papamichail, I., Papageorgiou, M., & Messmer, A. (2010). Optimal Motorway Traffic Flow Control Involving Variable Speed Limits and Ramp Metering. *Transportation Science*, *44*(2), 238–253. https://doi.org/10.1287/trsc.1090.0314

Cassidy, M. J., & Rudjanakanoknad, J. (2005). Increasing the capacity of an isolated merge by metering its on-ramp. *Transportation Research Part B: Methodological*, *39*(10), 896–913. https://doi.org/10.1016/j.trb.2004.12.001

Chu, T. D., Miwa, T., & Morikawa, T. (2014). Modeling Speed Adjustment Behavior of Merging Vehicles at Urban Expressway Merging Sections. *Procedia - Social and Behavioral Sciences*, *138*, 116–126. https://doi.org/10.1016/j.sbspro.2014.07.187

Cook, A. R., Pretty, R. L., & Cleveland, D. E. (1970). *Evaluation of the effectiveness of ramp metering operations* (No. TrS-2) (p. 142).

Costa, M., Simone, A., Vignali, V., Lantieri, C., Bucchi, A., & Dondi, G. (2014). Looking behavior for vertical road signs. *Transportation Research Part F: Traffic Psychology and Behaviour*, *23*, 147–155. https://doi.org/10.1016/j.trf.2014.01.003

CROW. (2017). *Richtlijn informatievoorziening op dynamische informatiepanelen*. CROW.

Daamen, W., Loot, M., & Hoogendoorn, S. (2010). Empirical Analysis of Merging Behavior at Freeway On-Ramp. *Transportation Research Record: Journal of the Transportation Research Board*, *2188*, 108–118. https://doi.org/10.3141/2188-12

Department for Transport. (2015). *Facts on Road Fatalities* (p. 10). Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/448037/road-fatalities-2013-data.pdf

Dutta, A., Fisher, D. L., & Noyce, D. A. (2004). Use of a driving simulator to evaluate and optimize factors affecting understandability of variable message signs. *Transportation Research Part F: Traffic Psychology and Behaviour*, *7*(4–5), 209–227. https://doi.org/10.1016/j.trf.2004.09.001

European Commission. (2017, May 14). Statistics – accidents data - Mobility and transport - European Commission. Retrieved May 14, 2017, from /transport/road_safety/specialist/statistics_en

Fatema, T., & Hassan, Y. (2013). Probabilistic Design of Freeway Entrance Speed-Change Lanes Considering Acceleration and Gap Acceptance Behavior. *Transportation Research Record: Journal of the Transportation Research Board*, *2348*, 30–37. https://doi.org/10.3141/2348-04

Fitch, G. M., Lee, S. E., Klauer, S., Hankey, J., Sudweeks, J., & Dingus, T. (2009). *Analysis of Lane-Change Crashes and Near-Crashes*. Department of transportation.

Freeway Geometric Design for Active Traffic Management in Europe. (n.d.), 96.

Fuller, R. (2000). The task-capability interface model of the driving process. *Recherche - Transports - Sécurité*, *66*, 47–57. https://doi.org/10.1016/S0761-8980(00)90006-2

Highways Agency. (2004). *Controlled Motorways. Safe roads, Reliable journeys, informed travelers* (Summary report) (p. 21). Bristol.

Hossain, M., & Muromachi, Y. (2013). A real-time crash prediction model for the ramp vicinities of urban expressways. *IATSS Research*, *37*(1), 68–79. https://doi.org/10.1016/j.iatssr.2013.05.001

Hössinger, R., & Berger, W. J. (2012). Comprehension of new instructions for car drivers in merging areas. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(2), 152–161. https://doi.org/10.1016/j.trf.2011.12.009

Hwang, S. Y., & Park, C. H. (2005). MODELING OF THE GAP ACCEPTANCE BEHAVIOR AT A MERGING SECTION OF URBAN FREEWAY. *Proceedings of the Eastern Asia Society for Transportation Studies*, *5*, 16.

Jeihani, M., NarooieNezhad, S., & Bakhsh Kelarestaghi, K. (2017). Integration of a driving simulator and a traffic simulator case study: Exploring drivers' behavior in response to variable message signs. *IATSS Research*, *41*(4), 164–171. https://doi.org/10.1016/j.iatssr.2017.03.001

Jin, P. J., Fang, J., Jiang, X., DeGaspari, M., & Walton, C. M. (2017). Gap metering for active traffic control at freeway merging sections. *Journal of Intelligent Transportation Systems*, *21*(1), 1–11. https://doi.org/10.1080/15472450.2016.1157021

Kennisinstituut voor Mobiliteitsbeleid. (2012). *Invloed van omgevingscondities op benutting*.

Kita, H. (1999). A merging–giveway interaction model of cars in a merging section: a game theoretic analysis. *Transportation Research Part A: Policy and Practice*, *33*(3–4), 305–312. https://doi.org/10.1016/S0965-8564(98)00039-1

Kline, T. J. B., Ghali, L. M., Kline, D. W., & Brown, S. (1990). Visibility Distance of Highway Signs among Young, Middle-Aged, and Older Observers: Icons Are Better than Text. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *32*(5), 609–619. https://doi.org/10.1177/001872089003200508

Knapper, A., Christoph, M., Hagenzieker, M., & Brookhuis, K. (2015). Comparing a driving simulator to the real road regarding distracted driving speed, 22.

Kondyli, A., & Elefteriadou, L. (2009). Driver Behavior at Freeway-Ramp Merging Areas: Focus Group Findings. *Transportation Research Record: Journal of the Transportation Research Board*, *2124*, 157–166. https://doi.org/10.3141/2124-15

Kondyli, A., & Elefteriadou, L. (2011). Modeling Driver Behavior at Freeway-Ramp Merges. *Transportation Research Record: Journal of the Transportation Research Board*, *2249*, 29–37. https://doi.org/10.3141/2249-05

Kondyli, A., & Elefteriadou, L. (2012). Driver behavior at freeway-ramp merging areas based on instrumented vehicle observations. *Transportation Letters*, *4*(3), 129–142. https://doi.org/10.3328/TL.2012.04.03.129-141

Kononov, J., Durso, C., Reeves, D., & Allery, B. (2012). Relationship Between Traffic Density, Speed, and Safety and Its Implications for Setting Variable Speed Limits on Freeways. *Transportation Research Record: Journal of the Transportation Research Board*, *2280*, 1–9. https://doi.org/10.3141/2280-01

Koppa, R. J. (2001). Chapter 3 Human factors. In N. Gartner, C. J. Messer, & A. K. Rathi (Eds.), *Traffic flow theory: A state-of-the-art report* (pp. 70–101).

Lai, C.-J. (2010). Effects of color scheme and message lines of variable message signs on driver performance. *Accident Analysis & Prevention*, *42*(4), 1003–1008. https://doi.org/10.1016/j.aap.2009.12.002

Larsson, A. F. (2013). Automation and the nature of driving, 91.

Laureshyn, A., Svensson, Å., & Hydén, C. (2010). Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation. *Accident Analysis & Prevention*, *42*(6), 1637–1646. https://doi.org/10.1016/j.aap.2010.03.021

Lee, C., & Abdel-Aty, M. (2008). Testing Effects of Warning Messages and Variable Speed Limits on Driver Behavior Using Driving Simulator. *Transportation Research Record: Journal of the Transportation Research Board*, *2069*, 55–64. https://doi.org/10.3141/2069-08

Li, S., Xiang, Q., Ma, Y., Gu, X., & Li, H. (2016). Crash Risk Prediction Modeling Based on the Traffic Conflict Technique and a Microscopic Simulation for Freeway Interchange Merging Areas. *International Journal of Environmental Research and Public Health*, *13*(11), 1157. https://doi.org/10.3390/ijerph13111157

Lighthill, M. J., & Whitham, G. B. (1955). On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *229*(1178), 317–345. https://doi.org/10.1098/rspa.1955.0089

Liu, C., & Wang, Z. (2012). Determination of Onramp Weaving Length for Resolving Merging Dilemma. *International Journal of Transportation Science and Technology*, *1*(1), 49–60. https://doi.org/10.1260/2046-0430.1.1.49

Liu, C., & Wang, Z. (2013). Ramp Metering Influence on Freeway Operational Safety near On-ramp Exits. *International Journal of Transportation Science and Technology*, *2*(2), 87–94. https://doi.org/10.1260/2046-0430.2.2.87

Liu, R. (2011). Modelling Motorway Merge: The Current Practice in the UK and Towards Establishing General Principles. *Procedia - Social and Behavioral Sciences*, *16*, 184–195. https://doi.org/10.1016/j.sbspro.2011.04.441

Louah, G., Daucher, D., Conde-Céspedes, P., Bosc, F., & Lhuillier, J.-P. (2011). Traffic Operations at an Entrance Ramp of a Suburban Freeway First Results. *Procedia - Social and Behavioral Sciences*, *16*, 162–171. https://doi.org/10.1016/j.sbspro.2011.04.439

Lu, X.-Y., Varaiya, P., Horowitz, R., Su, D., & Shladover, S. E. (2010). A new approach for combined freeway Variable Speed Limits and Coordinated Ramp Metering (pp. 491–498). IEEE. https://doi.org/10.1109/ITSC.2010.5625107

Luoma, J., Rämä, P., Penttinen, M., & Anttila, V. (2000, April 20). Effects of variable message signs for slippery road conditions on reported driver behaviour.pdf. Elsevier Science Ltd.

Ma, M., Yang, Q., Liang, S., & Li, Z. (2015). Integrated Variable Speed Limits Control and Ramp Metering for Bottleneck Regions on Freeway. *Mathematical Problems in Engineering*, *2015*, 1–17. https://doi.org/10.1155/2015/313089

Marczak, F., Daamen, W., & Buisson, C. (2013). Key Variables of Merging Behaviour: Empirical Comparison between Two Sites and Assessment of Gap Acceptance Theory. *Procedia - Social and Behavioral Sciences*, *80*, 678–697. https://doi.org/10.1016/j.sbspro.2013.05.036

Mars, F., & Navarro, J. (2012). Where We Look When We Drive with or without Active Steering Wheel Control. *PLoS ONE*, *7*(8), e43858. https://doi.org/10.1371/journal.pone.0043858

McCartt, A. T., Northrup, V. S., & Retting, R. A. (2004). Types and characteristics of ramp-related motor vehicle crashes on urban interstate roadways in Northern Virginia. *Journal of Safety Research*, *35*(1), 107–114. https://doi.org/10.1016/j.jsr.2003.09.019

Michaels, R. M., & Fazio, J. (1989). Driver Behavior Model of Mergirg. *Transportation Research Board*, (1213), 7.

Michon, J. A. (1985). A Critical View of Driver Behavior Models: What Do We Know, What Should We Do? In L. Evans & R. C. Schwing (Eds.), *Human Behavior and Traffic Safety* (pp. 485–524). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4613-2173-6_19

Mollu, K., Cornu, J., Brijs, K., Van Der Linden, M., de Boer, J., & Brijs, T. (2016). Gantries or Cantilevers for Route Guidance on a Reorganized Arterial Road? A Before Study of Route Choice Effectiveness Using a Traffic Sign Simulator (Case Study). *Transportation Research Procedia*, *14*, 4277–4285. https://doi.org/10.1016/j.trpro.2016.05.399

Murphy, G., & Greene, C. M. (2017). Load theory behind the wheel; perceptual and cognitive load effects. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *71*(3), 191–202. https://doi.org/10.1037/cep0000107

Najm, W. G., Stearns, M. D., Howarth, H., Koopmann, J., & Hitz, J. (2006). *Evaluation of an automotive rear-end collision avoidance system* (Final report No. DOT-VNTSC-NHTSA-06-01) (p. 425). Department of transportation. Retrieved from https://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2006/HS910569.pdf

Nevada Department of Transportation. (2013, December). Managed Lanes and Ramp Metering Part 4: Ramp Metering Performance Measurement Plan.

Nissan, A., & Koutsopoulosb, H. N. (2011). Evaluation of the Impact of Advisory Variable Speed Limits on Motorway Capacity and Level of Service. *Procedia - Social and Behavioral Sciences*, *16*, 100–109. https://doi.org/10.1016/j.sbspro.2011.04.433

Nobukawa, K., Bao, S., LeBlanc, D. J., Zhao, D., Peng, H., & Pan, C. S. (2016). Gap Acceptance During Lane Changes by Large-Truck Drivers—An Image-Based Analysis. *IEEE Transactions on Intelligent Transportation Systems*, *17*(3), 772–781. https://doi.org/10.1109/TITS.2015.2482821

Nygårdhs, S. (2011). Literature review on variable message signs (VMS) 2006–2009, 41.

Oka, N., Yoshino, K., Yamamoto, K., Takahashi, H., Li, S., Sugimachi, T., … Kato, T. (2015). Greater Activity in the Frontal Cortex on Left Curves: A Vector-Based fNIRS Study of Left and Right Curve Driving. *PLOS ONE*, *10*(5), e0127594. https://doi.org/10.1371/journal.pone.0127594

Olson, P. L. (1989). Driver Perception Response Time. https://doi.org/10.4271/890731

PROFFITT, D. R., & WADE, M. M. (1998). CREATING EFFECTIVE VARIABLE MESSAGE SIGNS: HUMAN FACTORS ISSUES, 26.

Rajaonah, B., Tricot, N., Anceaux, F., & Millot, P. (2008). The role of intervening variables in driver–ACC cooperation. *International Journal of Human-Computer Studies*, *66*(3), 185–197. https://doi.org/10.1016/j.ijhcs.2007.09.002

Rämä, P., & Kulmala, R. (2000, April 20). Effects of variable message signs for slippery road conditions on driving speed and headways.pdf. Elsevier Science Ltd.

Regan, M. A., Horberry, T., & Stevens, A. (2014). Part II: Measurement of driver acceptance. In *Driver Acceptance of new technology theory, Measurement and optimisation* (p. 89). Surrey: Ashgate Publishing Limited. Retrieved from https://www.researchgate.net/profile/Lisa_Dorn/publication/266822337_The_Profile_of_Emotional_Designs_A_Tool_for_the_Measurement_of_Affective_and_Cognitive_Responses_to_In-Vehicle_Innovations_Robert_Edmunds_Lisa_Dorn_and_Lee_Skrypchuk_in_Regan_A_2014_Driver_Acceptance_/links/54b3d8860cf2318f0f968ee8/The-Profile-of-Emotional-Designs-A-Tool-for-the-Measurement-of-Affective-and-Cognitive-Responses-to-In-Vehicle-Innovations-Robert-Edmunds-Lisa-Dorn-and-Lee-Skrypchuk-in-Regan-A-2014-Driver-Acceptan.pdf

Riener, A., Zia, K., Ferscha, A., Ruiz Beltran, C., & Minguez Rubio, J. J. (2013). Traffic flow harmonization in expressway merging. *Personal and Ubiquitous Computing*, *17*(3), 519–532. https://doi.org/10.1007/s00779-012-0505-6

Rijkswaterstaat. (2017). *Handreiking Bewegwijzeringsschema's* (p. 119).

Rijkswaterstaat. (2018, March 29). Uw vraag aan Rijkswaterstaat 180319-000474.

Sahami, S., & Sayed, T. (2010). Insight into Steering Adaptation Patterns in a Driving Simulator. *Transportation Research Record: Journal of the Transportation Research Board*, *2185*, 33–39. https://doi.org/10.3141/2185-05

Sarvi, M., Kuwahara, M., & Ceder, A. (2007). Observing freeway ramp merging phenomena in congested traffic. *Journal of Advanced Transportation*, *41*(2), 145–170. https://doi.org/10.1002/atr.5670410203

Shinar, D., & Vogelzang, M. (2013). Comprehension of traffic signs with symbolic versus text displays. *Transportation Research Part F: Traffic Psychology and Behaviour*, *18*, 72–82. https://doi.org/10.1016/j.trf.2012.12.012

Smulders, S. (1990). Control of freeway traffic flow by variable speed signs. *Transportation Research Part B: Methodological*, *24*(2), 111–132. https://doi.org/10.1016/0191-2615(90)90023-R

State of New York Department of Transportation. (2011). *VMS Guidelines Aug 2011.pdf* (p. 64).

Sun, J., Li, Z., & Sun, J. (2015). Study on traffic characteristics for a typical expressway on-ramp bottleneck considering various merging behaviors. *Physica A: Statistical Mechanics and Its Applications*, *440*, 57–67. https://doi.org/10.1016/j.physa.2015.08.007

SWOV. (2012). *factsheet volgtijd en verkeersveiligheid* (Factsheet) (p. 5). Leidschendam: Stichting wetenschappelijk onderzoek verkeersveiligheid. Retrieved from https://www.swov.nl/sites/default/files/publicaties/gearchiveerde-factsheet/nl/factsheet_volgtijd_gearchiveerd.pdf

Toledo, T., Koutsopoulos, H. N., & Ben-Akiva, M. (2007). Integrated driving behavior modeling. *Transportation Research Part C: Emerging Technologies*, *15*(2), 96–112. https://doi.org/10.1016/j.trc.2007.02.002

Trafikverket. (2018, April 19). Road markings ärende #559487 hos Kontaktcenter.

van Nes, N., Brandenburg, S., & Twisk, D. (2010). Improving homogeneity by dynamic speed limit systems. *Accident Analysis & Prevention*, *42*(3), 944–952. https://doi.org/10.1016/j.aap.2009.05.002

Wang, R., Hu, J., & Zhang, X. (2016). Analysis of the Driver's Behavior Characteristics in Low Volume Freeway Interchange. *Mathematical Problems in Engineering*, *2016*, 1–9. https://doi.org/10.1155/2016/2679516

World Health Organization. (2017, January 5). WHO _ Road traffic injuries.

Yang, H., & Ozbay, K. (2011). Estimation of Traffic Conflict Risk for Merging Vehicles on Highway Merge Section. *Transportation Research Record: Journal of the Transportation Research Board*, *2236*, 58–65. https://doi.org/10.3141/2236-07

Zheng, Z., Ahn, S., Chen, D., & Laval, J. (2013). The effects of lane-changing on the immediate follower: Anticipation, relaxation, and change in driver characteristics. *Transportation Research Part C: Emerging Technologies*, *26*, 367–379. https://doi.org/10.1016/j.trc.2012.10.007

Zheng, Z., Ahn, S., & Monsere, C. M. (2010). Impact of traffic oscillations on freeway crash occurrences. *Accident Analysis & Prevention*, *42*(2), 626–636. https://doi.org/10.1016/j.aap.2009.10.009

Zhou, M., & Sisiopiku, V. (1997). Relationship Between Volume-to-Capacity Ratios and Accident Rates. *Transportation Research Record: Journal of the Transportation Research Board*, *1581*, 47–52. https://doi.org/10.3141/1581-06

Appendix A Post drive questionnaire

Start of Block: Block 1

Info Bedankt voor uw deelname aan dit onderzoek. De volgende vragenlijst is bedoeld om informatie te verzamelen over de deelnemers van dit onderzoek en uw persoonlijke ervaring met het rijden in de rijsimulator en de bebording die u hierin zag.

De vragenlijst is anoniem en de gegevens worden uitsluitend voor dit onderzoek gebruikt.

Info Deelnemer ID

____

Q1 De volgende vragen gaan over uw algemene ervaring met het rijden in de rijsimulator.

Q2 Hoe realistisch vond u de ervaring van het rijden in de simulator?

- ○ Erg realistisch (1)
- ○ Realistich (2)
- ○ Neutraal (3)
- ○ Niet realistisch (4)
- ○ Helemaal niet realistisch (5)

Q3 Vind u dat u heeft gereden zoals u dit normaal ook zou doen?

○ Ja (1)

○ Nee (2)

Display This Question:

If Vind u dat u heeft gereden zoals u dit normaal ook zou doen? = Nee

Q3b Waarom reed u anders dan wat u normaal zou doen?

____

End of Block: Block 1

Start of Block: Vragen bebording

Info De volgende vragen hebben betrekking tot de duidelijkheid van de bebording die u tijdens het rijden in de simulator heeft gezien.

Voor elk bord word gevraagd hoe duidelijk u deze vond, gevolgd door een korte uitleg van uw keuze. Vervolgens word gevraagd naar uw voorkeur tussen twee varianten van de bebording, wederom word een korte uitleg van uw keuze gevraagd.

Q4

Hoe duidelijk vond u de bovenstaande bebording?

○ Erg duidelijk (1)

○ Begrijpbaar (2)

○ Neutraal (3)

○ Niet begrijpbaar (4)

○ Erg onduidelijk (5)

Display This Question:

If Hoe duidelijk vond u de bovenstaande bebording? = Erg duidelijk

Or Hoe duidelijk vond u de bovenstaande bebording? = Begrijpbaar

Q4a Waarom vindt u het bord duidelijk? (geef een kort antwoord)

____

Display This Question:

If Hoe duidelijk vond u de bovenstaande bebording? = Niet begrijpbaar

Or Hoe duidelijk vond u de bovenstaande bebording? = Erg onduidelijk

Q4b Waarom vindt u het bord onduidelijk? (geef een kort antwoord)

____

Q5 Denkt u dat u uw afstand tot uw voorganger heeft aangepast na het zien van dit bord?

- ○ Ja (1)
- ○ Nee (2)
- ○ Weet ik niet (3)

Q6 Denkt u dat u uw snelheid heeft aangepast na het zien van dit bord?

- ○ Ja (1)
- ○ Nee (2)
- ○ Weet ik niet (3)

End of Block: Vragen bebording

Start of Block: Block 4

Q7

Hoe duidelijk vindt u de bovenstaande bebording?

- ◯ Erg duidelijk (1)
- ◯ Begrijpbaar (2)
- ◯ Neutraal (3)
- ◯ Niet begrijpbaar (4)
- ◯ Erg onduidelijk (5)

Display This Question:

If Hoe duidelijk vindt u de bovenstaande bebording? = Erg duidelijk

Or Hoe duidelijk vindt u de bovenstaande bebording? = Begrijpbaar

Q7a Waarom vindt u het bord duidelijk? (geef een kort antwoord)

____

Display This Question:

If Hoe duidelijk vindt u de bovenstaande bebording? = Niet begrijpbaar

Or Hoe duidelijk vindt u de bovenstaande bebording? = Erg onduidelijk

Q7b Waarom vindt u het bord onduidelijk? (geef een kort antwoord)

____

Q8 Vindt u dat u uw afstand tot uw voorganger hebt aangepast na het zien van dit bord?

- Ja (1)
- Nee (2)
- Weet ik niet (3)

Q9 Vindt u dat u uw snelheid heeft aangepast na het zien van dit bord?

- Ja (1)
- Nee (2)
- Weet ik niet (3)

End of Block: Block 4

Start of Block: Block 5

Q10 Tijdens uw rit in de rijsimulator zag u twee verschillende ontwerpen van de bebording. Een boven aanzicht, en een ontwerp dat gebruik maakt van zogenoemde 'chevron markering'.

Welke variant vond u het duidelijkst?

(1)

(2)

Q11 Verklaar uw antwoord

____

End of Block: Block 5

Start of Block: Block 6

Info Tijdens het rijden zag u twee vormen van chevron markering. Het verschil tussen beide varianten is de volgorden waarin de chevron pijlen knipperen (van boven naar beneden en vice versa).

Q12 Is dit verschil u opgevallen tijdens het rijden in de simulator?

- Ja (1)
- Nee (2)

Q13 Bij welke van de borden die gebruik maken van chevron markering vond u het het duidelijkst wat er van u verwacht werd?

○ 

(1)

○ 

(2)

○ Geen voorkeur (3)

Q14 Verklaar uw antwoord

____

End of Block: Block 6

Start of Block: Deelnemer informatie

Q15 Wat is uw geslacht?

○ Man (1)

○ Vrouw (2)

Q16 Wat is uw leeftijd

____

Q17 Hoogte behaalde opleidingsniveau (diploma)

- ◯ Voortgezet onderwijs (1)
- ◯ Bachelor (2)
- ◯ Master (3)

Q18 U bent:

- ◯ Student (1)
- ◯ Werkende (2)

Q19 Hoeveel jaren rijervaring heeft u?

- ◯ 0 tot 1 jaar (1)
- ◯ 1 tot 5 jaar (2)
- ◯ 5 tot 10 jaar (3)
- ◯ Meer dan 10 jaar (4)

Q20 Hoeveel kilometer rijd u gemiddeld op jaarbasis?

- ○ 0 tot 4.999 km (1)
- ○ 5.000 tot 9.999 km (2)
- ○ 10.000 tot 14.999 km (3)
- ○ 15.000 tot 19.999 km (4)
- ○ 20.000 tot 25.000 km (5)
- ○ meer dan 25.000 km (6)

Q21 Maakt u gebruik van cruise control tijdens het rijden op de snelweg?

- ○ Nee (1)
- ○ Ja, soms (2)
- ○ Ja, altijd (3)

Q22 Wat denkt u dat het doel is van dit onderzoek? (kort antwoord)

____

End of Block: Deelnemer informatie

Start of Block: Block 7

Info Voor het volgende onderdeel word u gevraagd om uw mening met betrekking tot enkele stellingen

Q23 Ik ervaar regelmatig dat ik het gevoel heb dat er te weinig ruimte is om veilig in te voegen

- Sterk mee oneens (1)
- Mee oneens (2)
- Neutraal (4)
- Mee eens (5)
- Sterk mee eens (7)

Q24 Ik ben van mening dat een oplossing zoals "gap metering" een toegevoegde waarde heeft voor de verkeersveiligheid

- Sterk mee oneens (1)
- Mee oneens (2)
- Neutraal (4)
- Mee eens (5)
- Sterk mee eens (7)

Q24 Ik ervaar de boodschap/instructies van "gap metering" borden als duidelijk

- Sterk mee oneens (1)
- Mee oneens (2)
- Neutraal (4)
- Mee eens (5)
- Sterk mee eens (7)

Q26 Ik ben van mening dat een oplossing zoals "gap metering" te veel zal afleiden tijdens het rijden

- Sterk mee oneens (1)
- Mee oneens (2)
- Neutraal (4)
- Mee eens (5)
- Sterk mee eens (7)

Q27 Ik zal mij tijdens het rijden op de snelweg houden aan instructies zoals gegeven op de "gap metering" borden

- Sterk mee oneens (1)
- Mee oneens (2)
- Neutraal (4)
- Mee eens (5)
- Sterk mee eens (7)

Q28 Ik ben van mening dat "gap metering" borden mij alert maken voor het feit dat een andere auto in gaat voegen

- ◯ Sterk mee oneens (1)
- ◯ Mee oneens (2)
- ◯ Neutraal (4)
- ◯ Mee eens (5)
- ◯ Sterk mee eens (7)

End of Block: Block 7

Start of Block: Block 5

Info Bedankt voor uw deelname aan dit onderzoek.

End of Block: Block 5

Appendix B Pairwise comparison of the mean headway between scenarios

Multiple Comparisons						
(I) Condition	(J) Condition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Base	Square	2,45067	4,95958	1,000	-12,6334	17,5348
	Chevron top bottom	3,29967	4,87661	1,000	-11,5321	18,1314
	Chevron bottom top	,63990	4,95958	1,000	-14,4442	15,7240
	Square + VSL	-21,68623*	4,94378	,000	-36,7223	-6,6502
	Chevron top bottom + VSL	-6,32953	4,95958	1,000	-21,4136	8,7546
	Chevron bottom top + VSL	,43679	4,96358	1,000	-14,6595	15,5330
Square	Base	-2,45067	4,95958	1,000	-17,5348	12,6334
	Chevron top bottom	,84900	5,00005	1,000	-14,3582	16,0562
	Chevron bottom top	-1,81078	5,08099	1,000	-17,2641	13,6426
	Square + VSL	-24,13690*	5,06557	,000	-39,5434	-8,7304
	Chevron top bottom + VSL	-8,78021	5,08099	1,000	-24,2336	6,6732
	Chevron bottom top + VSL	-2,01389	5,08490	1,000	-17,4791	13,4514
Chevron top bottom	Base	-3,29967	4,87661	1,000	-18,1314	11,5321
	Square	-,84900	5,00005	1,000	-16,0562	14,3582
	Chevron bottom top	-2,65977	5,00005	1,000	-17,8669	12,5474
	Square + VSL	-24,98590*	4,98438	,000	-40,1454	-9,8264
	Chevron top bottom + VSL	-9,62920	5,00005	1,000	-24,8364	5,5780
	Chevron bottom top + VSL	-2,86288	5,00402	1,000	-18,0821	12,3564
Chevron bottom top	Base	-,63990	4,95958	1,000	-15,7240	14,4442
	Square	1,81078	5,08099	1,000	-13,6426	17,2641
	Chevron top bottom	2,65977	5,00005	1,000	-12,5474	17,8669
	Square + VSL	-22,32612*	5,06557	,000	-37,7326	-6,9197
	Chevron top bottom + VSL	-6,96943	5,08099	1,000	-22,4228	8,4839

	Chevron bottom top + VSL	-,20311	5,08490	1,000	-15,6684	15,2621
Square + VSL	Base	21,68623*	4,94378	,000	6,6502	36,7223
	Square	24,13690*	5,06557	,000	8,7304	39,5434
	Chevron top bottom	24,98590*	4,98438	,000	9,8264	40,1454
	Chevron bottom top	22,32612*	5,06557	,000	6,9197	37,7326
	Chevron top bottom + VSL	15,35669	5,06557	,052	-,0498	30,7632
	Chevron bottom top + VSL	22,12301*	5,06949	,000	6,7046	37,5414
Chevron top bottom + VSL	Base	6,32953	4,95958	1,000	-8,7546	21,4136
	Square	8,78021	5,08099	1,000	-6,6732	24,2336
	Chevron top bottom	9,62920	5,00005	1,000	-5,5780	24,8364
	Chevron bottom top	6,96943	5,08099	1,000	-8,4839	22,4228
	Square + VSL	-15,35669	5,06557	,052	-30,7632	,0498
	Chevron bottom top + VSL	6,76632	5,08490	1,000	-8,6989	22,2316
Chevron bottom top + VSL	Base	-,43679	4,96358	1,000	-15,5330	14,6595
	Square	2,01389	5,08490	1,000	-13,4514	17,4791
	Chevron top bottom	2,86288	5,00402	1,000	-12,3564	18,0821
	Chevron bottom top	,20311	5,08490	1,000	-15,2621	15,6684
	Square + VSL	-22,12301*	5,06949	,000	-37,5414	-6,7046
	Chevron top bottom + VSL	-6,76632	5,08490	1,000	-22,2316	8,6989

Appendix C Pairwise comparison of mean speeds for zones

Mean speed - Scenario 1	Mean difference	Sig.
zone -100 to zone -50	0.687	0.407
zone -50 to zone 0	0.215	1.000
zone 0 to zone 50	0.042	1.000
zone 50 to zone 100	-0.187	1.000
zone 100 to zone 150	0.354	1.000
zone 150 to zone 200	2.078	0.001
zone 200 to zone 250	3.297*	0.000
zone 250 to zone 300	3.783*	0.003
zone 300 to zone 350	1.666*	0.934
zone 350 to zone 400	-1.216	1.000

Mean speed - Scenario 2	Mean difference	Sig.
zone -100 to zone -50	0.480	1.000
zone -50 to zone 0	0.730	1.000
zone 0 to zone 50	1.379	0.115
zone 50 to zone 100	1.157	0.214
zone 100 to zone 150	0.595	1.000
zone 150 to zone 200	1.059	1.000
zone 200 to zone 250	1.698	0.477
zone 250 to zone 300	3.662	0.266
zone 300 to zone 350	0.795	1.000
zone 350 to zone 400	-2.573	0.079

Mean speed - Scenario 3	Mean difference	Sig.
zone -100 to zone -50	1.283	0.846
zone -50 to zone 0	1.359*	0.050
zone 0 to zone 50	1.529*	0.006
zone 50 to zone 100	0.586	1.000
zone 100 to zone 150	-0.427	1.000
zone 150 to zone 200	1.240	0.269
zone 200 to zone 250	3.392*	0.011
zone 250 to zone 300	3.743*	0.025
zone 300 to zone 350	2.033	1.000
zone 350 to zone 400	-1.346	1.000

Mean speed - Scenario 4	Mean difference	Sig.
zone -100 to zone -50	1.314	0.751
zone -50 to zone 0	1.026	0.599
zone 0 to zone 50	0.980	1.000
zone 50 to zone 100	0.496	1.000
zone 100 to zone 150	0.435	1.000
zone 150 to zone 200	1.910	0.199
zone 200 to zone 250	3.453	0.059
zone 250 to zone 300	4.756	0.072
zone 300 to zone 350	-0.225	1.000
zone 350 to zone 400	-2.255	0.543

Mean speed - Scenario 5	Mean difference	Sig.
zone -100 to zone -50	0.360	1.000
zone -50 to zone 0	0.136	1.000
zone 0 to zone 50	0.645	1.000
zone 50 to zone 100	0.037	1.000
zone 100 to zone 150	-0.272	1.000
zone 150 to zone 200	-0.830	1.000
zone 200 to zone 250	-0.926	1.000
zone 250 to zone 300	0.700	1.000
zone 300 to zone 350	1.807	0.755
zone 350 to zone 400	-0.919	1.000

Mean speed - Scenario 6	Mean difference	Sig.
zone -100 to zone -50	0.745	1.000
zone -50 to zone 0	0.361	1.000
zone 0 to zone 50	0.062	1.000
zone 50 to zone 100	-0.209	1.000
zone 100 to zone 150	-0.161	1.000
zone 150 to zone 200	-0.013	1.000
zone 200 to zone 250	-1.200	1.000
zone 250 to zone 300	-1.110	1.000
zone 300 to zone 350	2.429	1.000
zone 350 to zone 400	-2.297	0.453

Mean speed - Scenario 7	Mean difference	Sig.
zone -100 to zone -50	0.103	1.000
zone -50 to zone 0	-0.142	1.000
zone 0 to zone 50	0.442	1.000
zone 50 to zone 100	0.802	1.000
zone 100 to zone 150	0.271	1.000
zone 150 to zone 200	-0.340	1.000
zone 200 to zone 250	-1.012	1.000
zone 250 to zone 300	-0.023	1.000
zone 300 to zone 350	0.787	1.000
zone 350 to zone 400	-1.017	1.000

Appendix D Pairwise comparison of lateral position per zone

Lateral position - Scenario 1	Mean difference	Sig.
zone -100 to zone -50	-0.026	1.000
zone -50 to zone 0	0.005	1.000
zone 0 to zone 50	0.013	1.000
zone 50 to zone 100	-0.005	1.000
zone 100 to zone 150	-0.012	1.000
zone 150 to zone 200	0.049	1.000
zone 200 to zone 250	-0.049	1.000
zone 250 to zone 300	1.079*	0.000
zone 300 to zone 350	.561*	0.000
zone 350 to zone 400	0.141	1.000

Lateral position- Scenario 2	Mean difference	Sig.
zone -100 to zone -50	0.016	1.000
zone -50 to zone 0	0.016	1.000
zone 0 to zone 50	0.042	1.000
zone 50 to zone 100	0.102	1.000
zone 100 to zone 150	0.127	0.234
zone 150 to zone 200	0.256	0.541
zone 200 to zone 250	.405*	0.001
zone 250 to zone 300	.617*	0.000
zone 300 to zone 350	.321*	0.020
zone 350 to zone 400	0.108	1.000

Lateral position- Scenario 3	Mean difference	Sig.
zone -100 to zone -50	0.024	1.000
zone -50 to zone 0	0.041	1.000
zone 0 to zone 50	0.128	1.000
zone 50 to zone 100	0.107	1.000
zone 100 to zone 150	0.101	1.000
zone 150 to zone 200	0.137	0.171
zone 200 to zone 250	.415*	0.003
zone 250 to zone 300	.573*	0.001
zone 300 to zone 350	.352*	0.028
zone 350 to zone 400	0.083	1.000

Lateral position- Scenario 4	Mean difference	Sig.
zone -100 to zone -50	0.021	1.000
zone -50 to zone 0	0.029	1.000
zone 0 to zone 50	0.100	1.000
zone 50 to zone 100	0.119	1.000
zone 100 to zone 150	0.183	1.000
zone 150 to zone 200	0.181	0.259
zone 200 to zone 250	.373*	0.002
zone 250 to zone 300	.666*	0.000
zone 300 to zone 350	.452*	0.008
zone 350 to zone 400	0.100	1.000

Lateral position- Scenario 5	Mean difference	Sig.
zone -100 to zone -50	0.008	1.000
zone -50 to zone 0	0.197	1.000
zone 0 to zone 50	0.216	1.000
zone 50 to zone 100	0.095	0.400
zone 100 to zone 150	0.086	1.000
zone 150 to zone 200	0.224	0.093
zone 200 to zone 250	.440*	0.000
zone 250 to zone 300	.456*	0.006
zone 300 to zone 350	0.147	1.000
zone 350 to zone 400	-0.043	1.000

Lateral position- Scenario 6	Mean difference	Sig.
zone -100 to zone -50	0.046	1.000
zone -50 to zone 0	0.067	1.000
zone 0 to zone 50	0.189	0.862
zone 50 to zone 100	0.207	0.599
zone 100 to zone 150	0.116	0.343
zone 150 to zone 200	.289*	0.008
zone 200 to zone 250	.523*	0.002
zone 250 to zone 300	0.329	0.068
zone 300 to zone 350	0.071	1.000
zone 350 to zone 400	-0.060	1.000

Lateral position- Scenario 7	Mean difference	Sig.
zone -100 to zone -50	0.106	1.000
zone -50 to zone 0	0.101	1.000
zone 0 to zone 50	0.078	1.000
zone 50 to zone 100	0.037	1.000
zone 100 to zone 150	0.090	1.000
zone 150 to zone 200	0.244	0.201
zone 200 to zone 250	.428*	0.001
zone 250 to zone 300	.406*	0.017
zone 300 to zone 350	0.149	1.000
zone 350 to zone 400	0.038	1.000