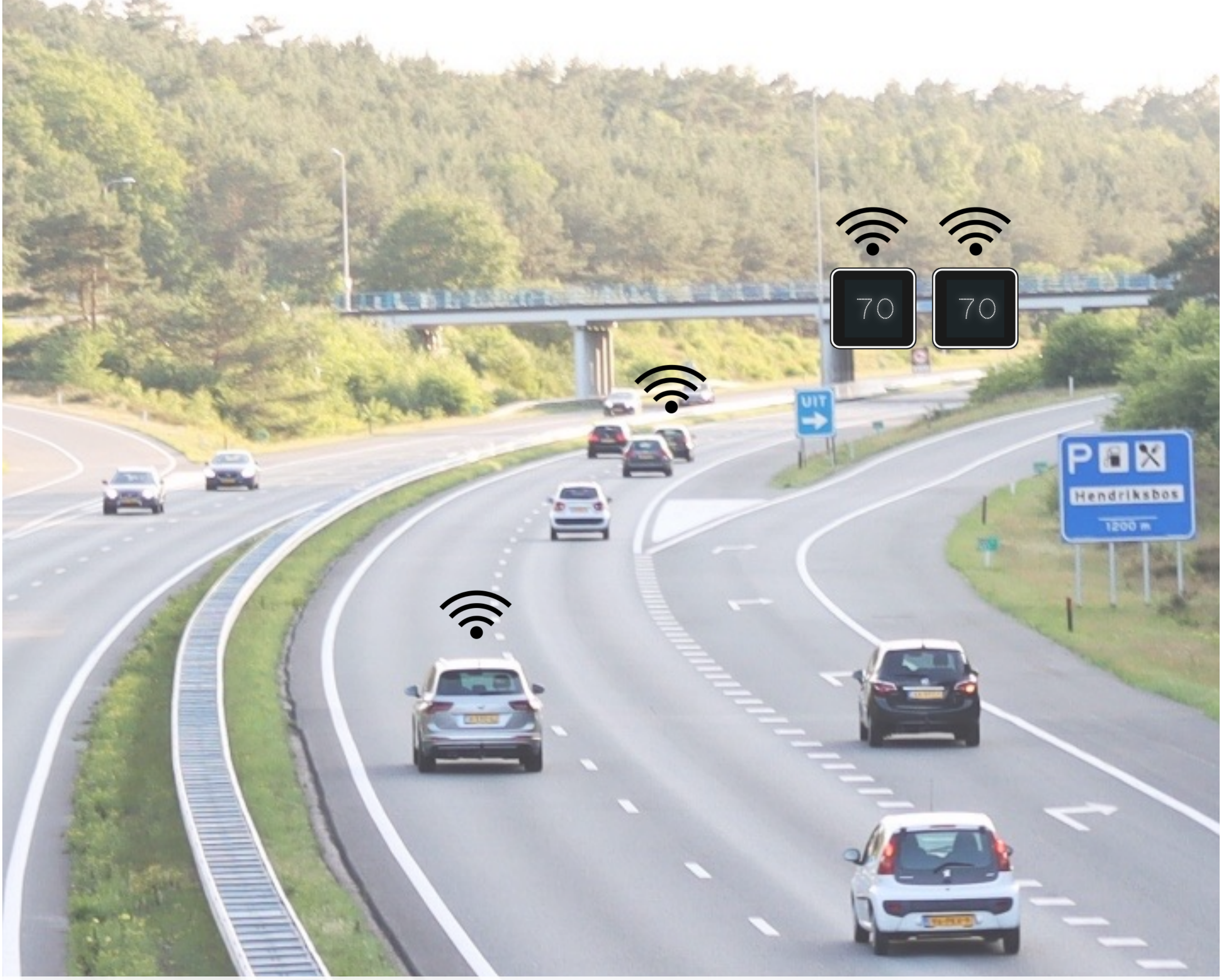
Driving behavior in mixed traffic in combination with variable speed limit

Master Thesis

J.S. Wiersma



TU Delft
SAMEN
Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Driving behavior in mixed traffic in combination with variable speed limit

Jitse Wiersma (4367383) [1]
Master Thesis Report

[1]MSc Transport, Infrastructure & Logistics
Delft University of Technology,

Project duration: August 2021 - February 2022
To be defended on: 11 February 2022

Graduation Committee:

Chair	Dr. ir. H. Farah	TU Delft	Transport & Planning
Daily supervisor	Ir. N. Reddy	TU Delft	Transport & Planning
Daily supervisor	Dr. ir. S.C. Calvert	TU Delft	Transport & Planning
External supervisor	Dr. ir. E. Papadimitriou	TU Delft	Values, Technology & Innovation
Company Supervisor	Drs. E. Schol	Rijkswaterstaat	Water, Verkeer & Leefomgeving

February 6, 2022

Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Preface

This thesis is the final requirement to obtain my master's degree in Transport, Infrastructure and Logistics at the Technical University of Delft. I started my journey in Delft in 2014 with the bachelor Systems Engineering, Policy Analysis & Management. During my bachelors, I realized that my interest is in the field of transportation and mobility. I decided to change the direction of my studies and start the masters of Transport, Infrastructure and Logistics in 2019. I would like to thank everyone who supported me or was (in)directly involved during my bachelors and masters. For this thesis project I would like to specially thank several people.

First, I would like to thank my supervision committee. I would like to thank my daily supervisor Nagarjun Reddy for our countless meetings during the whole process of the research. From the start Nagarjun Reddy was very actively involved and gave me the support I needed in terms of project process and content. Nagarjun Reddy always made time to meet and has been a constant source of motivation. His flexibility and creative and practical advice always helped me overcome struggles I encountered along the way. I would like to thank Haneen Farah, as the chair of the supervision committee she had a significant contribution to the research. Haneen Farah always encouraged me to think critically and guided me on the scientific part of the research. Besides, the experience of both Nagarjun Reddy and Haneen Farah on driving simulator studies helped to increase the quality of the driving simulator experiment. Furthermore, I would like to thank Simeon Calvert and Eleonora Papadimitriou for their constructive and extensive feedback during our meetings. Their feedback helped to further increase the relevance of the research, and they helped me to widen my perspective. Last but not least, I would like to thank by company supervisors Erna Schol and Boris van Waterschoot. They provided me with the opportunity to conduct this research in collaboration with Rijkswaterstaat. They gave me a chance to experience what it is like to work for Rijkswaterstaat and provided me with helpful contacts within their network. Besides, they improved the quality of the research by critically reviewing the research from a road authority's perspective and provided constructive scientific advice as well. I would like to thank all my committee members for helping me to finish this research in time. I appreciate that all of you respected my tight schedule because om my own commitments after my academic career. I am very grateful for the flexibility you all showed in terms of deadlines for receiving the report and planning meetings. This gave me the chance to perform the best I could.

Furthermore, I would like to thank Wouter Schakel, who helped me to implement the experiment in the driving simulator. Without his help, the driving simulator experiment would not have been possible.

Last, I would like to thank my family and friends for their support during my master thesis. I want to thank my parents for their unconditional love and support. They gave me the freedom and guidance to find my path in life. My friends from study, roommates, and may others for their friendship and making my time as a student just the best time I could have hoped for. I will cherish the good times forever. Special thanks go out to my girlfriend. She supported me in high and low times and managed to put up with me for the last three years, and hopefully many to come.

Jitse Wiersma Utrecht, February 2022

Executive summary

Introduction

With the advancement in both vehicle and infrastructure technology, vehicles are able to communicate and share information with the infrastructure and the other way around. A potential application of communication between vehicles and the infrastructure is providing information to upstream Connected and Automated Vehicles (CAVs) on upcoming Variable Speed Limits (VSLs). With upstream information CAV will be able to adjust their speed earlier and smoother which potentially could benefit the traffic safety and efficiency by increasing the overall speed compliance and speed adaptation to upcoming speed limits of the total traffic flow. Most of the studies make use of microscopic models to analyze the effect of communication technologies in mixed traffic. However, most microscopic models do not incorporate behavioral adaptation of HDV drivers in mixed traffic.

Previous literature on mixed traffic has found that human drivers tend to change their driving behavior when interacting with (partly) Automated Vehicles (AVs) on the road compared to when interacting with Human Driven Vehicles (HDVs). This means that introducing CAVs on the road provided with upstream information could lead to behavioral adaptations in the driving behavior of human drivers.

In order to make correct prognosis on the potential benefits in terms of traffic safety and efficiency of sharing information on the upcoming speed limits and foreseeing potential future challenges in mixed traffic the behavioral adaptations of human drivers should be known.

Therefore, the main research question of this study is:

How do human drivers change their car-following, lane-changing and speed adaption behavior in mixed traffic in combination with VSL on motorways?

The focus of this research is the effect of the presence of CAVs in combination with upstream information to CAVs on the driving behavior of HDV drivers. Drivers of unequipped cars (HDVs) receive the information on a speed limit adaptation via the VSL signs above the road whereas CAVs can receive information on the upcoming speed limit more upstream. The independent variables analyzed in this research are the penetration rate of CAVs and the distance of upstream information to CAVs. Next to this, the effect of driving style of the HDV driver on the change in driving behavior in the new driving context analyzed.

Method

To answer the main research question a driving simulator experiment was designed. The road segment that was used consisted out of a straight three lane motorway equipped with VSL and was based on the Dutch design guidelines and regulations. The VSL signs were placed with a spacing of 600m. A Variable Message Sign (VMS) warning for upcoming congestion was added to increase the credibility of the speed reduction. The design of the road segment is presented in Figure 1 including the speed strategy of the Advanced Traffic Management System (ATMS). The independent variables analyzed in this research are the penetration rate of CAV, the distance at which information is provided to CAVs and the driving style of the subject drivers.

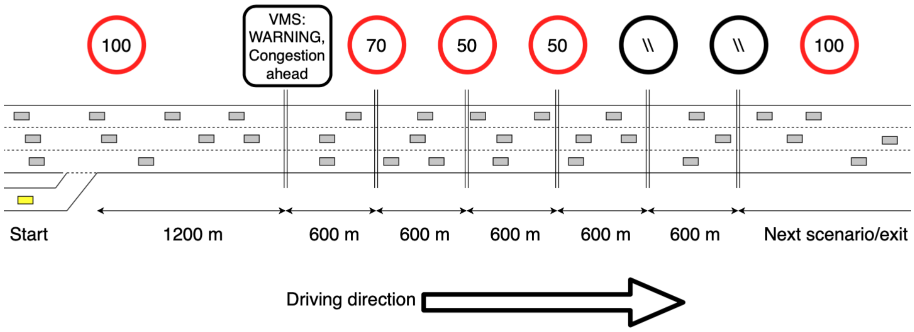


Figure 1: Road section

The CAVs were designed to behave differently compared to the HDVs in this research. CAVs were designed to not exceed the speed limit and adapt their speed from the moment they receive information on an upcoming speed limit. Next to this, the CAVs were designed to keep a safe Time Headway (THW). The behavior of HDVs was designed to be more heterogeneous in terms of speed compliance and car following behavior. The lane changing of both vehicles was similar.

For the penetration rate three levels were analyzed, 0%, 10% and 40%, reflecting the expected penetration rate for the years 2030 and 2050. For the distance upstream three levels were analyzed as well, 300m, 600m, and 900m. The reference point for the distances is the gantry with the VSL which presents the new speed limit. Considering only the levels with 10% and 40% could be combined with upstream information a total of 7 scenarios were created.

Each participant drove the scenarios twice, once before the break and once after the break. The order of scenarios presented to the participants were randomized within the two sessions. A total of 36 participants (27 males, 9 females) participated in the experiment.

Results

The driving behavior of the participants was investigated for the different road sections and described by various driving behavior indicators. The indicators used in this research to describe the driving behavior of subject drivers are the mean speed, section entry speed, speed compliance, THW, number of lane changes and duration of lane change.

For the indicators THW, number of lane changes and duration of lane change no significant differences were found between the different scenarios. For the speed indicators interesting differences were found.

The average speed profile per scenario is shown in Figure 2 from which the mean speed, section entry speed and speed compliance can be determined. From a visual inspection of Figure 2 it can be noticed that the approach section to the 70kmph speed limit, the 70kmph section and the first 50kmph show most interesting speed differences between the scenarios. These are sections where subject drivers decelerate with regard to the reduced speed limit posted on the VSL signs.

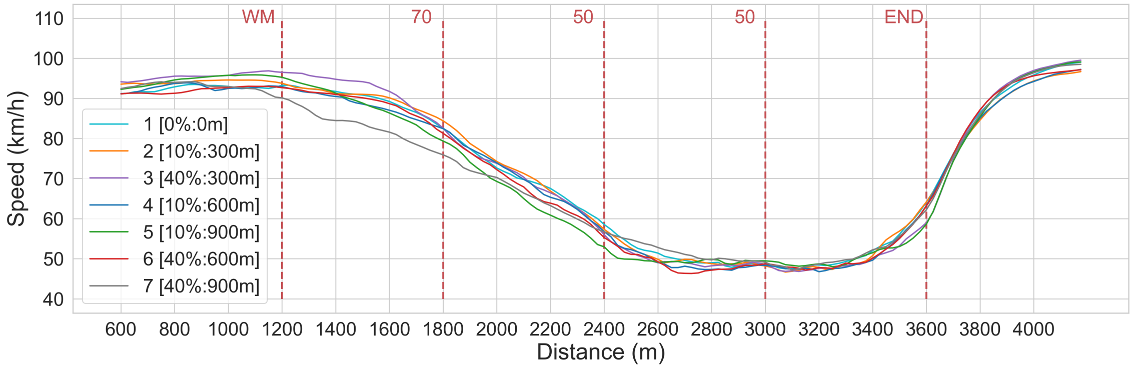


Figure 2: Visualization of average speed of all participants per scenario S[P:D] where S: scenario, P: penetration rate, D: distance upstream

When no upstream information (300m) is provided and for 600m upstream information no significant differences were found for the three penetration rate levels for either the mean speed, section entry speed and speed compliance. If the information is provided at a distance of 900m the mean speed reduced, section entry speed is reduced and speed compliance in increased for increasing levels of penetration rate. A penetration of 10% of CAVs decreases the mean speed in the 70 section by 7% from 69.6 to 64.7 kmph. Besides, the section entry speed of the 70 section decreases by 3.2 kmph and 5.6 kmph for the 50_1 section. The speed compliance increases for sections 70 and 50_1 by 3.2s and 2s. For a penetration of 40% a significant decrease in mean speed is observed in the approach section by 8% from 89.7 to 82.6 kmph, and the 70 section by 6%, from 69.6 to 65.8 kmph. Furthermore, the entry speed of the 70 section is lowered with 6.6 kmph and the speed compliance increases for the 70 section with 3.1s .

The biggest difference with varying levels of penetration rate is the location at which HDV drivers start to adapt their speed. For a penetration rate of 10% HDV drivers start to decelerate more upstream compared to 0%. When the penetration rate is increased to 40%, HDV drivers start to decelerate even more upstream compared to 0% and 40%.

The levels for upstream information were analyzed for two fixed levels of penetration rate. It was found that providing upstream information at a penetration rate of 10% only has a significant effect on the driving behavior of human drivers if a distance of 900m is applied. When the penetration rate increases to 40% a distance of 600m upstream information show significant reductions in mean speed, section entry speed and increase in speed compliance as well. If information is provided at a distance of 900m in combination with 10% penetration rate the mean speed is lowered by 8% from 70.08 to 64.76 kmph in the 70 section. Furthermore, the section entry speed decreases for the 70 section by 5.0 kmph and for the 50_1 section by 4.4 kmph. Besides, the speed compliance increases in the 70 by 3.9s.

In case the penetration rate of CAVs increases to 40%, significant results are found for both 600 and 900 meters of upstream information. With 600 meter of upstream information the mean speed is decreased in the approach section by 3% from 92.0 to 88.95 kmph. The section entry speed is lowered for the approach section by 3.8 kmph and no effect is found for speed compliance. With 900 meters of upstream information for more road sections significant differences are found. The mean speed is decreased in the approach and 70 section. In the approach section a decrease of 10% is realized from 92.0 to 82.61 kmph. In the 70 section the mean speed is lowered by 5%, from 69.2 to 65.8 kmph. The section entry speed in the approach section is lowered with 6.5 kmph and in the 70 section with 6.6 kmph. The speed compliance increases slightly for the 70 section with 2.1s but decreases in the 50_1 section with 5.3s.

In order to investigate the effect of driving style of subject drivers, the participants sample was divided over two driving style groups based on their self-reported driving style. Aggressive participants were selected on a low driving index and social drivers were selected on a high driving index. The run averages of the different indicators were tested per scenario between the two groups. None of the run averages was found to be statistically different between the two driving style groups.

Discussion and conclusion

For the effect of penetration rate it might be concluded that different levels of penetration rate of CAVs on itself does not induce behavioral adaptation whereas it does in combination with a large distance of upstream information. This means that just adding AVs to the total traffic does not necessarily results into safer and more efficient traffic.

For the effect of upstream information it might be concluded that providing upstream information on the speed limit has the most effect if it is provided at a large distance upstream of the actual VSL. Furthermore, the benefits of upstream information are expanded when more CAVs are present on the road. Thus, from this research it might be stated that combining a high penetration rate of CAVs with a large distance of upstream information could improve the traffic safety by slowing down traffic.

Although differences were expected between the two groups no difference in driving behavior was found in this research. This means that both groups behave identical in terms of driving behavior and behavioral adaptation. As a result, when designing a communication strategy between VSL and CAVs from this research it might be concluded that no special attention has to be paid to different driving style groups.

In conclusion, it is found that HDV drivers do not change their lane-changing and car-following behavior in mixed traffic in combination with VSL on motorways. However, a change in speed adaptation is observed in case a large distance is chosen at which the speed limit is shared with CAV. Human drivers tend to reduce their speed earlier in case the surrounding traffic drives slower as well. This results in an overall lower mean speed in a VSL road segment, a higher speed compliance and lower entry speeds at the VSL sign locations where a new speed limit becomes active.

Recommendations

From the results it could be concluded that providing upstream information to only part of the traffic could contribute to influencing the speed behavior of the total traffic flow without leading to negative behavioral adaptations in terms of more aggressive or unsafe driving behavior. In case a road authority would implement connectivity between the infrastructure and vehicles to communicate information on upcoming speed limits the following aspects should be taken into account. A large distance of upstream information should be considered in order to influence the behavior of surrounding traffic. In this research the largest distance researched was 900m. 900m is found to be a good distance since at this distance the speed behavior of HDV drivers was significantly reduced. 900m of upstream information already resulted in a change in driving behavior of HDV drivers at a penetration rate of 10% for CAVs. In case the penetration rate would further increase to 40% the effect on the driving behavior becomes even larger. This suggests that an increase in penetration rate would result in larger effects of behavioral adaptation.

Future research should focus on studying more levels for both penetration rate and distance of upstream information in a real-world context. Multiple field tests should be executed to verify the potential effects on speeding behavior of human drivers found in this research.

Contents

List of acronyms

ABS Anti-lock Breaking System
ACC Adaptive Cruise Control
ADAS Advanced Driver Assistance Systems
AV Automated Vehicle
ATMS Advanced Traffic Management System
CACC Cooperative Adaptive Cruise Control
CAV Connected and Automated Vehicle
DBQ Driving Behavior Questionnaire
DDT Dynamic Driving Task
HCM Highway Capacity Manual
HDV Human Driven Vehicle
I2V Infrastructure to Vehicle
ISA Intelligent Speed Adaptation
ITS Intelligent Transport System
MDSI Multidimensional Driving Style Inventory
MPC Model Predictive Control
ODD Operational Design Domain
OEDR Object and Event Detection and Response
PADI Pro-social and Aggressive Driving Inventory
THW Time Headway
TSR Traffic Sign Recognition
TTC Time-To-Collision
V2V Vehicle to Vehicle
VSL Variable Speed Limit
VMS Variable Message Sign

List of Figures

List of Tables

1. Introduction

Dutch motorways are intensively used, leading to negative effects such as crashes, time-loss and environmental damage. In the Netherlands the total costs of negative external effects of traffic in 2018 is estimated to be 28 billion euros (accidents: 17, congestion: 4, environmental: 7) (SWOV, 2020). One solution used in the past was to increase the capacity of the road network in order to relieve congestion. However, expanding the road network is most of the time impossible due to lack of available space. To overcome this problem, new technologies and innovations are introduced in the transport field to make the current network more efficient and safer (Pype et al., 2017).

Vehicles are under constant development, resulting in new forms of Advanced Driver Assistance Systems (ADAS) and (partly) automated driving. Developments in vehicle technology are generally introduced to either improve the driving experience or make driving safer. This is achieved by implementing warning or automation systems in vehicles to assist the driver (Ziebinski, Cupek, Grzechca, & Chruszczyk, 2017). These automation systems differ in terms of driving characteristics from human drivers (Sharma, Ali, Saifuzzaman, Zheng, & Haque, 2018). As a result, different forms of driving behavior are present on the road, leading to new forms of interactions between road users. Moreover, traffic management authorities are faced with a challenge having to deal with both human-driven and automated vehicles on the road, which have different requirements regarding the infrastructure.

Next to new vehicle technologies, advancements are made on the infrastructural level. Infrastructural innovations lead to new opportunities for road authorities to dynamically intervene according to the live traffic condition. Examples of so-called smart motorways are flexible congestion lanes, route advice on next to road message signs and dynamic speed adaptation (Jallow, Renukappa, & Alneyadi, 2019). These new intervention methods lead to an increase and/or change in information presented to the road users with the goal to change their behavior for safer and more efficient traffic. With the advancement in both vehicle and infrastructure technology, vehicles are able to communicate and share information with the infrastructure and the other way around (Sanguesa et al., 2015). In literature, different benefits of the connectivity between the infrastructure and vehicles are presented. From a traffic management perspective, the connectivity between the infrastructure and vehicles is twofold. First, connected vehicles can provide more detailed and real-time information. With this enriched information, the traffic management system can make better informed decisions on potential measures to make traffic flow more efficient and/or safe (Pan et al., 2021). Potential measures could be to temporarily change the speed limit or distribute traffic over different corridors. Secondly, the compliance to measures activated by the traffic management system can be enhanced by sending information directly to connected vehicles (Qi, Sun, Ma, Wang, & Yu, 2020).

1.1 Problem description

Driving is a constant interplay of the driver and his/her environment, and wherein developments in both infrastructure and vehicles lead to new situations and challenges. The effect of a technological innovation on traffic safety or traffic flow is partly dependent on the behavioral adaptation of humans. Humans are prone to modify their behavior according to their new situation (Smiley, 2000). These modifications to their behavior can either be conscious or sub-conscious. Besides, not all vehicles will be equipped with either automation and/or connectivity technologies, which means that human drivers and AVs have to be able to drive together on the same roads. Moreover, the information that is available for a vehicle, and its driver, will differ per vehicle type. This results in a situation where vehicles and drivers make decisions regarding their driving behavior based on different information.

In the coming years, the greatest share of drivers will not drive a vehicle which is connected to the infrastructure (Milakis, Snelder, Arem, Wee, & Correia, 2017). Therefore, it is of great importance to know how these traditional drivers are affected by vehicles which are connected and research potential behavioral adaptations of traditional drivers.

1.2 Research gap

With the introduction of CAV on the road, it is expected that HDV drivers might change their driving behavior. Literature exists on potential behavioral adaptations. A significant part of research focuses on the behavioral adaptation of HDV next to platoons. However, besides platooning, other features of CAV could influence the behavior of HDV as well. One of these features is the connectivity with the infrastructure and the provision of information from the infrastructure to CAV called Infrastructure to Vehicle (I2V) communication. This new form of communication on public roads could lead to an information asymmetry between CAV and HDV. Due to the time constraint, one specific application of connectivity between vehicles and the infrastructure is chosen as the main focus of this study. A commonly used technique for information provision on motorways is VSL. VSL is a technique that allows for flexible, remote, and manual or automatic adaptation of speed limits. With the help of I2V the adapted speed limit can be sent to CAV (in advance). Apart from the information asymmetry between the two vehicle types that arises, a difference in driving style factors between CAV and HDV leads to HDV drivers being exposed to new forms of driving behavior of surrounding vehicles. In the literature, benefits on traffic safety and efficiency are presented regarding the cooperation between VSL systems and CAVs. However, most of these studies make use of microscopic modelling and don't include potential behavioral adaptation. In most studies, behavior for CAV is added to the model, but the behavior of HDV drivers is not adjusted.

In order to have realistic insights into the benefits of the cooperation between VSL and, CAV a better understanding of the potential behavioral adaptation of HDV drivers is needed. An improved understanding will contribute to better microscopic models and thus lead to more realistic results. Moreover, if behavioral adaption is understood, countermeasures can be examined to overcome negative effects on traffic safety and flow.

1.3 Research questions

To fill the research gap, the main research question of this research is:

How do human drivers change their car-following, lane-changing and speed adaptation behavior in mixed traffic in combination with VSL on motorways?

To answer the main research question, the following sub questions are formulated:

1. What is the effect of the penetration rate of CAV on car-following, lane-changing and speed adaptation behavior of HDV in combination with VSL?
2. What is the effect of sharing the VSL with CAV at various distances upstream on car-following, lane-changing and speed adaptation behavior of HDV?
3. What is the effect of driving style of human drivers on car-following, lane-changing and speed adaptation behavior in mixed traffic in combination with VSL?
4. What practical insights for road authorities can be drawn from the identified changes in car-following, lane-changing behavior and speed adaptation?

The focus of this research is potential behavioral adaptation of human drivers in a context of mixed traffic where automated vehicles are able to communicate with the infrastructure. The potential behavioral adaptation is empirically researched with the help of a driving simulator. In this case, researching mixed traffic in combination with VSL can only be done in a driving simulator, due to the communication between the two systems is not yet present on the current motorways.

The first three sub-questions are answered with the help of the driving simulator experiment. For the first question, varying levels of penetration rate are analyzed. For the second question, varying levels of distances of upstream information are implemented. In case of the third question, all scenarios are analyzed for two driving style groups. A questionnaire on driving behavior will be used to select participants for the two groups. The last sub-question relates to the qualitative analysis of the results to find practical implications for road authorities.

1.4 Terminology and definitions

To answer the research questions, first some concepts used in the questions need to be defined.

The behavioral adaptation of HDV in mixed traffic is studied in this research. Therefore, the concepts of a HDV and a CAV need to be defined. A HDV is characterized by a vehicle without any in-vehicle driving warning/assistance systems. This means that the full Dynamic Driving Task (DDT) is executed by a human driver and that no warning systems are installed, and no use is made of applications with warning systems. This can be labelled as a level 0 automation (SAE, 2021b). The CAV is characterized by automated longitudinal control, referring to a level 1 automation. In this research CAV is defined as a vehicle equipped with a form of communication technology and an Adaptive Cruise Control (ACC) system. It is assumed that the ACC is activated, which means the vehicle has the control over the longitudinal behavior. Besides, adaptation in speed is regulated by the information provided by the infrastructure. Mixed traffic relates to the presence of both HDVs and CAVs as defined above.

Sharing speed limit information upstream relates to the communication technology to inform CAVs on the posted and changing speed limit. Road authorities can choose which type of communication technology they use and at which distance upstream of the VSL the information is provided. For HDVs the speed limit is only displayed on the VMS above the road. The distance at which HDV drivers start to adapt their speed is therefore dependent on the sight distance at which humans can detect and recognize the information on the VMS.

1.5 Scientific and societal contribution

The collaboration between automated vehicles and the infrastructure could be one of the solutions to tackle current traffic problems. A better understanding of the potential behavioral adaptation of human drivers in mixed traffic gives the scientific community more information on potential benefits of the connectivity between vehicles and the infrastructure. Besides, the scientific community will be able to better predict potential challenges in future traffic situations with mixed traffic. Moreover, information on a specific situation where connectivity is used results in a better understanding of the behavior of human drivers in those conditions.

For road authorities, the understanding of driving behavior and the interaction between automated vehicles and traditional human drivers is of great importance. With the expected increased penetration rate of automated vehicles, a better understanding is needed in order to ensure the safety and efficiency of the road network in the future. The adaptation of the road infrastructure can take several decades. This means that a better understanding of future traffic conditions leads to better adaptations and investments in the current and future traffic infrastructure.

1.6 Thesis outline

This thesis is built on the following chapters (see Figure 1.1):

Chapter 2 presents a summary of the literature review, including the state of the art on Intelligent Transport Systems (ITSs), driving behavior and mixed traffic. Besides, the insights into behavioral adaption in mixed traffic and ITS are combined to form a conceptual model. Furthermore, based on the literature, hypotheses are formulated for the research questions presented in section 1.3

Chapter 3 aims to provide the research methodology of this research. This includes the setup of the driving simulator, the scenario design and data processing and analyzing methods.

Chapter 4 describes the data collection process from the driving simulator and surveys. Next to this, the data analysis and processing strategy is discussed.

Chapter 5 presents the descriptive insights of the participant sample and the validity of the driving simulator experiment. These insights are based on the data collected from the surveys.

Chapter 6 gives insight in the descriptive statistics of the outputs of the actual driving simulator experiment.

Chapter 7 presents the testing of hypotheses formulated in chapter 3. To test the hypothesis, statistical tests are used to examine if the results described in chapter 7 are significant.

Chapter 8 discusses the results to the research questions and tries to provide a conclusion on the main research question. Afterwards, the chapter provides a reflection on the research and presents the limitations.

Chapter 9 discusses the recommendations for future research and practical recommendations to road authorities involved with traffic management systems.

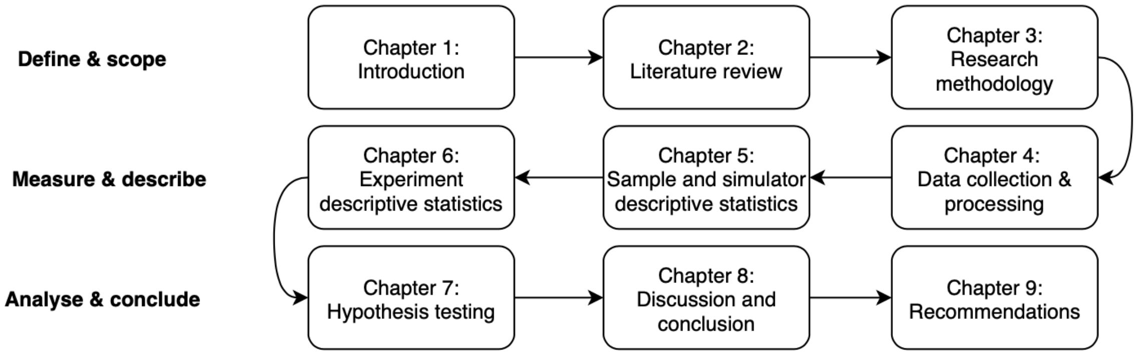


Figure 1.1: Thesis outline

2. Literature Review

In the following literature review, the state of the art on ITSs, driving behavior and mixed traffic is summarized. First, the ITSs are discussed. Second, the concept of mixed traffic and driving behavior research is reviewed. Last, research into behavioral adaptation in mixed traffic is presented.

2.1 Literature study methodology

To find relevant literature search engines, Google Scholar and Scopus were used. The initial search terms that were used are a combination of "mixed traffic" and "traffic safety". These were extended with notions as "automated and connected vehicles", "behavioral adaptation", "driving simulator" and "variable speed limit". Afterwards more specific search terms were used to find literature on specific concepts such as "car-following", "lane-changing", "speed compliance" in combination with "variable speed limit" and "mixed traffic". Forward and backward snowballing tactic was used to find relevant studies. For general driving studies and VSL a search setting of approximately 20 years back was used and for more modern concepts as CAVs more recent studies were used (10 years old). Next to the search engines, relevant literature was provided by contacts from Rijkswaterstaat and the Technical University Delft.

2.2 Intelligent Transport System

The advancement in sensing, computation, recognition and control technologies have enabled the introduction and enhanced the development of ITSs. ITS is an overarching concept that contains systems where vehicles interact with each other and the environment. The objective of most ITSs is either to improve the driving experience, increase traffic safety by reducing the risk of fatalities and injuries in road traffic, improve the efficiency of the road network or decrease the adverse effects of traffic on the environment (Williams, 2008). The goals are achieved by a cooperation of multiple actors like drivers, vehicles, road operators and traffic managers. The quality of an ITS is dependent on the access and collection of data, processing the data and the communication between different stakeholders. A note has to be made that these systems often do not work in isolation but operate simultaneously in the same environment. The sensing systems of ITSs for road traffic can be divided into two categories. The first category includes systems which relate to the state or driving condition of a vehicle. These systems range from collecting data on the vehicle's technical condition to the position of the vehicle on the road (Guerrero-Ibáñez, Zeadally, & Contreras-Castillo, 2018). The second category is related to systems on an infrastructural level. These systems measure the state of the network and traffic condition. Two major applications within the field of ITS are an ATMSs and the connectivity and automation of vehicles. Where connectivity and automation refer to the first category and ATMS refers to the second category. In the following subsections, the two applications are set out and the potential beneficial simultaneous application is discussed.

2.2.1 Automation and connectivity

AVs are able to (partly) drive without intervention of a human. The Society of Automotive Engineers differentiates six levels of automation, where level zero refers to no automation and level five to full automation without any human intervention (SAE, 2021b). The different levels of automated driving are defined by the entity which takes control of the DDT, Object and Event Detection and Response (OEDR) and DDT fallback. An entity can either be a human or the automation system. The conditions/situations for which a system is designed to operate is called the Operational Design Domain (ODD). In the first three levels the driver is still responsible for the OEDR whereas in levels 3 to 5 the systems takes care of the entire DDT. Only in level 4 and 5 no human intervention is needed for the vehicle to drive, where level 4 automation has a limited ODD and a level 5 is able to operate under all conditions. A summary of the levels of automation is given below in Figure 2.1.

Level	Name	Narrative definition	DDT: Sustained lateral and longitudinal vehicle motion control	DDT: OEDR	DDT fallback	ODD
Driver* performs part or all of the *DDT						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 2.1: SAE levels of automation (SAE, 2021b)

Connected vehicles are able to communicate with other vehicles and/or the infrastructure. I2V is used to send information from the infrastructure to connected vehicles and the other way around. Connectivity with the infrastructure can be used to inform connected vehicles on e.g. local speed regulations and information on upcoming traffic situations (Sanguesa et al., 2015). Vehicle to Vehicle (V2V) communication is used to coordinate local interactions between vehicles. Connectivity with other vehicles can be used to coordinate a vehicle's condition and to support negotiation between vehicles (Eiermann, Sawade, Bunk, Breuel, & Radusch, 2020). The different types of cooperation between participating entities can be divided over four categories (SAE, 2021a). The classes below are arranged from low (A) to high (D) level of cooperation.

- Class A: Status sharing
- Class B: Intent-sharing

- Class C: Agreement-seeking
- Class D: Prescriptive

Various types of communication technologies are being developed and tested in the EU COOPER (co-operative networks for intelligent road safety) program, ranging from broadcast to cell-based to dedicated short-range communication technologies (Böhm, Pfliegl, & Frötscher, 2008). These technologies offer road authorities different ways to communicate information to and support different levels of cooperation with connected vehicles. A section of road infrastructure can be classified based on the level of support it can provide. Carreras et al. (2018) distinguish five levels of infrastructure based on its support level, from "no support" to "cooperative driving".

				Digital information provided to AVs			
	Level	Name	Description	Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Conventional infrastructure	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs.				
Conventional infrastructure	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.	X			
Digital infrastructure	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
Digital infrastructure	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time.	X	X	X	
Digital infrastructure	A	Cooperative driving	Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

Figure 2.2: Road support levels (Carreras et al., 2018)

An application of connectivity and automation is Cooperative Adaptive Cruise Control (CACC). CACC is a combination of an ACC system which takes care of the longitudinal driving task, and a connectivity technology which allows for communication and cooperation with other vehicles and/or the infrastructure. CACC can be labeled as a level 1 automation, since only the longitudinal driving task is executed by the automation system. Cooperation between different vehicles allows multiple connected vehicles to form a string, contributing to more stable and efficient traffic flow, smaller headway and enhanced traffic safety (Olia, Abdelgawad, Abdulhai, & Razavi, 2016). Cooperation between the infrastructure and vehicles can be used to inform vehicles on traffic conditions and local traffic regulations. This cooperation can be classified as a class B cooperation, while the infrastructure provides information on the upcoming speed regulations to vehicles through communication. In case the receiving vehicle is mandated to comply with the communicated message, it is classified as a class D cooperation.

Thus far, the majority of research into CAVs mostly focused on the benefits to the overall network performance. Olia et al. (2016) showed that CAVs can contribute to an improvement at network-wide level to mobility, enhanced safety and reduced greenhouse gas emissions.

Aria et al. (2016) found that in a CAV scenario, traffic capacity improved by 8.09% and speeds increased by 8.48% on a crowded German motorway in peak hours, together improving the total travel time by 9.00%. Besides, CAVs and platoons of connected vehicles are found to be able to act as a damper in traffic flows which prevents the decrease of inter-vehicle spacing and thereby decreasing the chance of chain collisions (Sharma, Zheng, Kim, Bhaskar, & Mazharul Haque, 2021; Wang et al., 2020).

2.2.2 Traffic management & variable speed limit

ATMSs are systems that allow for dynamically regulating non-recurrent and recurrent congestion based on real-time and predicted traffic conditions (Kurzhanskiy & Varaiya, 2010). The systems include strategies as temporary shoulder use, speed harmonization, junction control, speed harmonization, dynamic signing and rerouting. The first ATMS in the Netherlands on a motorway already dates back to the 1980s and consisted of a queue warning system (Middelham, 2003). An example of a VMS with variable speed limits is shown in Figure 2.3.

One important feature of an ATMS is VSL. VSL is a widely used technique that allows for flexible, remote, and manual or automatic adaptation of speed limits. Several types of VSL systems are implemented around the globe with different objectives and type of operations. The main goal of VSL is to improve traffic safety and flow by increasing homogeneity of traffic and reducing speed violations (van Nes, Brandenburg, & Twisk, 2010; Grumert, Tapani, & Ma, 2018). Multiple implementations with different objectives exist around the world. Some examples are:

1. Congestion Warning Systems to warn and/or decrease speed of up stream traffic on congestion/slow speeds down stream on a motorway.
2. Homogenization Systems which are activated to lower the speed limit and temporarily increase the capacity when the traffic flow is near to capacity of the motorway segment.
3. Environmental Impact Zones which either relocate traffic or decrease speed limits in specific problematic areas.
4. Lane-merging zones where VSL tries to impact the lane-distribution and speeds near on- and off-ramps at motorways.
5. Multi Objective Traffic Management Systems are present where combinations of above stated applications are implemented. (D. Frejo, Papamichail, Papageorgiou, & De Schutter, 2019)

Figure 2.3: Example of VSL sign

VSL is based on control mechanisms and rule-based logic, using predetermined thresholds regarding flow and speed. In the last decade, a more advanced method is invented to overcome the reactive nature of the rule-based method and makes use of Model Predictive Control (MPC). Future traffic conditions as bottlenecks can be predicted and anticipated on before they occur with help of MPC (Khondaker & Kattan, 2015b)

The main benefits of VSL are threefold. The first benefit is regarding safety. One of the main goals of VSL is to homogenize the traffic by reducing the speed variance of vehicles. Lower speed variances reduces rear-end collisions on motorways (Strömgren & Lind, 2016; Z. Li, Liu, Wang, & Xu, 2014). Besides, reduced speed variances discourage drivers to make lane-changes, which reduces the risk of collisions (Khondaker & Kattan, 2015a). The second benefit is the capability of VSL to restore the capacity of a motorway by slowing down traffic. As a result, potential bottlenecks can be prevented or delayed (Hegyi, Schutter, & Hellendoorn, 2005; Strömgren & Lind, 2016). In contrast, the capacity can also be reduced as a result of applying below-critical speed limits (Papageorgiou, Kosmatopoulos, & Papamichail, 2008). Below critical speed limits are reduced speed limits when applied at under-critical occupancy of a motorway. As a result, the traffic is constrained by the speed limit, which decreases the capacity of the motorway. The third benefit concerns environmental issues. Congestion is a cause of higher GHG emissions such as CO_2, NO_x and different types of "Particulate Matter" and has therefore negative environmental impact. Preventing congestion can contribute to lowered emissions from traffic. Furthermore, speed limits can be lowered to reduce other emissions such as noise (Zegeye, De Schutter, Hellendoorn, & Breunesse, 2010).

2.2.3 Combined VSL and CAV operation

The combination of VSL and connectivity and automation of vehicles is of special interest, while a cooperation and simultaneous application could lead to better results regarding traffic safety and efficiency (Khondaker & Kattan, 2015a). Before the benefits of a cooperation between VSL and CAVs are presented, the minimum requirements for both the infrastructure, and the vehicle should be addressed.

From an infrastructure perspective, two aspects are needed. First, a road section has to feature a VSL system. This includes the physical sensors on the road, the signs above the road, and the non-physical traffic management system responsible for the speed control strategy. Second, the infrastructure must be equipped with communication technology. From a vehicle perspective again two technologies are needed for an integrated system. First, the vehicle needs to be able to receive information from the infrastructure with the help of the previous stated communication technologies. Second, the automation system responsible for the longitudinal control of the vehicle needs to be able to act on the information (speed limit) presented to it. In this research, a vehicle equipped with a form of communication technology and an ACC system can be described as a CAV. Communication between vehicles is not taken into account.

The cooperation or simultaneous application of VSL and CAVs could lead to further improvement of traffic safety and efficiency. Different directions of improvement are presented in literature. CAV can provide real-time and precise information on vehicle trajectories to the VSL management system to improve the decision-making on the adaptation of the speed limit to the real-time traffic condition (Pan et al., 2021). Besides, CAVs could have a positive effect on the total traffic flow and safety if the speed recommendation/limit will be respected more (Qi et al., 2020). Furthermore, with the presence of I2V, speed strategies can be implemented by the road authority directly on vehicles, whereas VSL signs can only present the posted speed limit to drivers with the help of signs (Malikopoulos, Hong, Park, Lee, & Ryu, 2019). Moreover, CAVs can be informed on bottlenecks or speed limits downstream to slow down traffic before arriving at the visual VSL (Khondaker & Kattan, 2015a).

Li et al. (2016) have studied the direct impact of the integration of VSL and ACC systems on the risk of rear-end collisions. This study was done by making use of a microscopic modeling technique in MATLAB. They modified the Intelligent Driver Model with ACC behavior and included a VSL strategy. Afterwards, an I2V system was introduced to connect the ACC behavior with the VSL strategy. In the experiment they compared four different scenarios of no control, ACC only, VSL only, and the integrated VSL and ACC system. The risk of rear-end collision was then measured by the integrated Time-To-Collision (TTC) of all vehicles. ACC only showed a reduction of 58.6% and VSL only showed a reduction of 65.3% integrated TTC compared to the base scenario of no control. The combined VSL and ACC system resulted in an even further reduction of 77.3% compared to the base scenario, proving that an integrated system can lead to significant safer traffic regarding rear-end collisions.

2.3 Mixed traffic and driving behavior

Some benefits of the introduction of CAVs were discussed in the section above. Despite CAVs promise to take over the driving task completely, HDVs will be predominantly existing on roads in the coming years (). A transition period will follow, with increasing levels of automation and penetration rates of CAVs. During the transition period, CAVs have to be able to drive together with traditional vehicles and the other way around in a safe way on public roads. The mixture of HDVs and CAVs on the road is called mixed traffic.

To understand the interactions in mixed traffic and to be able to analyze these interactions, the concept of driving behavior has to be explained. Driving behavior in the context of a motorway can be described by car-following, lane-changing and speed compliance behavior (Hogema, 1999). These notions are explained in the subsections below. Afterwards, driving characteristics of a CAV and a HDV are presented to show how these vehicle types differ from each other.

2.3.1 Car-following behavior

Car-following is the driving task where one vehicle follows another one on a single lane or road section, and where the following car's speed is influenced by the leading vehicle. The driving task is relatively simple. However, rear-end crashes are the most common accident on motorways around the world (Golob, Recker, & Alvarez, 2004; Wu & Thor, 2015) and is the cause of 33% of all fatal accidents on Dutch national roads (Davidse, Louwerse, & Duijvenvoorde, 2019).

Car-following behavior can be described by the time-headway and inter-vehicle distances. For manually driven cars, the time-headway usually fluctuates when driving behind another car due to slight changes in speed. ACC and CACC could help to reduce fluctuations in time-headway by automatically adapting the speed of the following car based on the preferred time-headway. The preferred THW of human drivers differs per person and can therefore be best described by THW-distributions (Moridpour, 2014). Loulizi, Bichiou & Rakha (2019) found that THW decreases with increasing speed. For vehicle behind vehicle following behavior, they found an average THW around 1.2s on motorways with speeds ranging from 90-108 kmph. These results are similar to a previous study into preferred THW by Brackstone, Waterson & McDonald (2009).

Defining a threshold to distinguish car-following traffic from free-flowing traffic proved to be a difficult matter, resulting in different thresholds being defined and used in literature. Various factors play a role when defining a threshold such as road conditions (flow rate, speed limit, road geometric) weather conditions and vehicle characteristics (Ayres, Li, Schleuning, & Douglas, 2001). Furthermore, THW thresholds can vary per driver based on driver characteristics, such as age and driving experience. Brackstone et al., (2009) concluded that drivers are inconsistent in their preferred choice of THW which makes it even harder to define a clear threshold.

In the US Highway Capacity Manual (HCM) following traffic is defined by the percentage of time spent under a time-headway of 3s. An empirical study by Vogel (2002) researched the tipping-point where the speed of two following vehicles correlates. She found a threshold of 6s. However, in her study a one-lane road section was used, excluding overtaking maneuvers. During overtaking maneuvers, a following car's speed can be influenced by the leading vehicles, but is soon able to drive at their own desired speed again when it has overtaken the leading vehicle. The Department for Transport in the UK uses four THW groups (<2s, 2-4s, 4-6s, >6s) for categorizing heavy good vehicles based on their following behavior (Department for Transport, 2021). This indicates that a headway larger than 6 seconds is used as a tipping point for free-flowing traffic on motorways.

2.3.2 Lane-changing behavior

Lane-changing activity relates to shifting lanes on a road section with more than one lane. Lane-changing has gained increasing attention due to the findings that lane-changes have a substantial impact on traffic safety and efficiency. Jin (2013) revealed that lane-changes play a crucial role on traffic breakdown/capacity drop. Laval & Daganzo (2006) explained the capacity drop on motorways after lane-changes by the temporal difference in speed of the lane-changer's vehicle and target lane and the limited capability of lane changers to accelerate. In addition, lane-changers spend more time below the critical threshold of 1s THW (M. Guo, Wu, & Zhu, 2018). Next to the effect of lane-changes to traffic safety and efficiency, lane-changing temporarily increases the workload for both the driver that performs the lane-change (Kim, Hwang, Yoon, & Park, 2013) and the driver that is being overtaken (Teh, Jamson, & Carsten, 2012).

Lane changes can be divided into mandatory lane changes which are needed for drivers to reach their destination and discretionary lane changes which are made to improve the driving condition. For modelling mandatory lane changes, often gap acceptance models are applied. However, for discretionary lane changes more factors and strategies play a role including speed difference, safety, comfort or information on the downstream road/traffic situation (Keyvan-Ekbatani, Knoop, & Daamen, 2016). A similar strategy does not automatically result in the same choice of lane. For example, drivers can have different opinions on which lanes he/she perceives as most safe, and thus a safety strategy can lead to a different lane choice per driver. On motorway sections without any on- or off-ramps or weaving sections, lane changes can be classified as discretionary.

Lane-changing behavior on motorways can be described by the number of lane-changes per distance, the lead and lag gap before and after a lane-change and the overtaking duration (Hill, Elefteriadou, & Kondyli, 2014). The number of lane-changes made by a driver is positively correlated with an aggressive driving style (M. Guo et al., 2018). To model lane-changing behavior, often gap acceptance theory is used. This theory describes which gaps in terms of distance or time to leading and lag vehicles on the destination lane are accepted and which are rejected (Marczak, Daamen, & Buisson, 2013). The total gap is the sum of the lead and lag gap and the merging vehicle. In mixed traffic HDV drivers tend to make more over-taking actions with increasing penetration rates of CAVs (Zhong, Lee, Nejad, & Lee, 2020).

2.3.3 Speed compliance

Speed compliance is the concept of whether drivers adhere to the speed limit or at least not exceed the speed limit. Traffic safety is strongly related to speed because both crash risk and crash severity increase with higher speeds (Aarts & van Schagen, 2006). Speeding is very common and on average 40-50% of drivers exceed the speed limit in free-flowing traffic (OECD/ECMT, 2006; Rijkswaterstaat Water, Verkeer en Leefomgeving, 2020). Determinants for the rate of compliance of drivers on a certain road section are credibility of the speed limit, risk perception, enforcement and surrounding traffic.

Credibility relates to the degree to which a speed limit is perceived as acceptable by most road users, taking into account road characteristics and environment conditions (Goldenbeld & van Schagen, 2007). Speed limits that are perceived as credible result in a higher speed compliance (van Nes et al., 2010).

Risk perception relates to the subjective perception of risk drivers experience while driving and is not related to the objective crash data. A higher perceived risk leads to lower speeds and less speeding. However, the heterogeneity of perceived risk and risk tolerance can result in large speed variances between drivers (Yao, Carsten, & Hibberd, 2020).

Enforcement is the activity of penalizing drivers who exceed the speed limit. Enforcement of a speed limit has multiple road safety benefits. First, speed limits are effective in reducing excessive speed violations. Secondly, enforcement leads to a reduction of the average speed driven. Last of all, it has a positive effect on the overall speed compliance. As a result, enforcement helps to reduce crash rates (Soole, Watson, & Fleiter, 2013).

Drivers are affected by the actions or driving behavior of vehicles in their surrounding. Drivers are prone to subconscious imitating behavior of traffic in their vicinity. This imitating behavior is called herding and can be explained by the contagion theory of Connolly & Aberg (1993). The contagion theory describes three types of drivers related to speeding, those who will obey the speed limit, those who will always speed and imitators. Imitators copy the driving behavior of other drivers in terms of speed choice. Empirical evidence is found by Mohammadi, Arvin, Khattak & Chakraborty (2021) who found that 16% of subject drivers start to accelerate when being overtaken by a faster vehicle. Next to this, Arthur (2011) showed that next to traffic density and speed of ambient traffic flow, the contagion theory was accurate regarding speed choice. Following the contagion theory, intervention measures to improve overall speed compliance should focus predominately on the habitual speeders because imitators will follow automatically.

2.3.4 Speed compliance under Variable Speed Limit

An important determinant of the effects or benefits of a VSL implementation is the compliance of drivers to the posted speed limit (Hellinga & Mandelzys, 2011). When all adhere to the posted speed limit the average speed and speed variance are reduced. Speed compliance under active VSL is similar to speed compliance under fixed speed limits (Ardeshiri & Jeihani, 2014). However, speed compliance at the first few VSL signs is commonly lower due to the inability of drivers to decelerate quickly (C. Lee & Abdel-Aty, 2008). A recent study by

Varotto, Jansen, Bijleveld & van Nes (2021b) showed that compliance to the posted speed on VSL can be predicted by low speeds before the gantry, proportion eyes-on-road, distance between consecutive gantries and approaching a slower leading vehicle. Another study by Harms & Brookhuis (2016) researched the ability of drivers to comply with a changing speed limit on a familiar road. They found that not all drivers were able to adhere to the posted speed limit as a result of the inability of drivers to detect a change in speed limit showed on the VSL signs. A potential explanation is given by Charlton & Starkey (2013) who found that driving in a familiar environment leads to driving without awareness, in other words, driving without paying attention to potential changes of road features. Matowicki & Pribyl (2021) revealed that speed compliance under VSL is influenced by the driver's understanding of the systems and the education of the driver.

Other studies have investigated the behavior of drivers under VSL. Boyle & Mannering (2004; 2008) found that drivers tend to compensate for the lost time due to the lowered speed limit. As a result, the average speed of drivers is higher after the VSL road section. Moreover, false or unnecessary speed reduction by VSL can impact the trust and compliance during subsequent events (Lees & Lee, 2007). Besides, malfunctions of the VSL systems could lead to dangerous situations where due to the malfunction and thus no warning or speed limit reduction, drivers do not expect a critical event on a motorway (Martens, 2013).

2.3.5 Driving characteristics in mixed traffic

HDVs and CAVs differ greatly in terms of driving characteristics and thus in driving behavior. These differences in driving behavior therefor lead to new challenges related to traffic safety. Differences between CAVs and HDVs related to driving characteristics in the context of motorway driving are reaction time, aggressiveness/risk taking propensity and driver compliance (Sharma et al., 2018).

Reaction time is the time it takes for drivers to process the information presented to them and act on it. Reaction time for human drivers can fluctuate significantly since it is highly dependent on other human factors as distraction/attention, drowsiness, age etc. (Mehmood & Easa, 2009). Automation promises to decrease the reaction time in traffic because it is not influenced by the human factors stated above. However, a study by Mikridis, Mattas, Anesiadou & Ciuffo (2021) who experimented with 22 commercial vehicles equipped with ACC systems showed that response time of ACC is similar to humans and by no means instantaneous.The reaction time of following CAVs can be reduced with the help of communication or cooperation between connected vehicles because only the first vehicle in a string will need to react to a situation.

Aggressiveness or risk-taking behavior is behavior where drivers intentionally put other persons at risk. It can vary from honking and flashing lights to dangerous lane-changing actions, short following distance and blocking other drivers (Özkan, Lajunen, Parker, Sümer, & Summala, 2010). The driving behavior of CAVs can vary by changing the settings of the automation system by either the driver or the vehicle manufacturer. Examples are the input for preferred THW when driving in ACC mode and gap-acceptance of vehicles equipped with automated lane-changing systems.

Driver compliance is another human factor that differentiates between HDVs and CAVs. Where CAVs are programmed to follow traffic rules as speed limits, stopping for a red light etc. drivers of HDVs tend to be less strict with following the rules (Sharma, Zheng, Bhaskar, & Haque, 2019). A technology already in place to support human drivers is Intelligent Speed Adaptation (ISA). ISA makes use of automated Traffic Sign Recognition (TSR) which is used to automatically recognize traffic signs and present the information to the driver. These systems rely on cameras to visually detect/recognize traffic signs. ISA will be mandatory from 2022 for all new vehicles in the European Union (European Parlement, 2019). However, reliable, automated recognition remains a complex task and is dependent on things as quality of the sign, weather condition and sight distance (Hoferlin & Zimmermann, 2009).

2.4 Behavioral adaptation in mixed traffic

With the introduction of CAVs on public roads, it is expected that HDV drivers will adapt their driving behavior (Beza & Zefreh, 2019). Behavioral adaptation is a known concept in the transport field, and it covers the intrinsic nature of humans to adapt to new situations or conditions (Smiley, 2000). A common definition used in the transport field is *"any change of driver, traveller, and travel behaviors that occur following user interaction with a change to the road traffic system, in addition to those behaviors specifically targeted by the initiators of the change"* (Kulmala & Rämä, 2013, p.20). A well-known example is the introduction of Anti-lock Breaking System (ABS), which is part of the stability system of vehicles, controlling the wheel spin under heavy breaking actions. Before the introduction of the technology, it was expected to significantly contribute to traffic safety. However, the contribution to traffic safety was reduced by a change in behavior of drivers due to later and harder breaking actions and shorter following distances (Sagberg, Fosser, & Sætermo, 1997).

When introducing a new technology close attention has to be paid to the behavioral adaptation in order to be able to anticipate on potential negative behavioral adaptations. Some studies have found that behavioral adaptations are present in mixed traffic. Most of these studies focus either on the car-following or lane-changing behavior of HDV drivers. Multiple studies have found that HDV drivers decrease their THW when driving next to a platoon of CAV (Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014; Yang, Farah, Schoenmakers, & Alkim, 2019; Gouy, 2013; Schoenmakers, Yang, & Farah, 2021). Furthermore, HDV drivers feel more confident driving behind a platoon of CAVs resulting in shorter THW (Rahmati, Khajeh Hosseini, Talebpour, Swain, & Nelson, 2019). The THW and inter-vehicle distance are very important factors on motorways as most accidents on motorway are rear-end crashes (SWOV, 2013) caused by short time-headway (Davis & Swenson, 2006). A positive behavioral adaptation is that HDV drivers who follow a CAV exhibit lower speed variance and a lowered volatility in terms of acceleration, resulting in more stable driving behavior (Mahdinia, Mohammadnazar, Arvin, & Khattak, 2021). Guo et al. (2020) used a simulator study to research the behavior of HDV drivers when driving in the vicinity of a platoon with respect to their lane change behavior. They found that drivers postpone their planned lane change when driving next to a platoon with small THW (0.8s). Lee, Oh & Hong (2018) found that the presence of CAV platoons increase the lane change preparation time of HDV drivers because identifying appropriate gaps is more difficult. Moreover, they found that HDV drivers make more extreme lane changes when they change lane into a CAV platoon. In this study extreme lane-changes are categorized by steering velocity and steering magnitude of the HDV driver while making the lane-change.

A summary of the literature regarding behavioral adaptation in mixed traffic is given below in Table 2.1.

Table 2.1: Summary of research into behavioral adaptation in mixed traffic

Author(s)	Year	Main findings	Type
Longitudinal driving behavior			
Gouy et al.	2014	1. HDVs show shorter average and minimum THW when driving next to (truck) platoons with short THW (0.3s) compared to long THW-platoon (1.4s) and no platoon 2. HDVs spend more time under critical THW of 1s. next to short THW-platoon (45.8%) compared to long THW-platoon (34.0%)	Driving simulator
Schoenmakers et al.	2021	HDV drivers significantly lowered THW when driving next to platoons on "continuous access lane" (2.47s), "limited access lane with buffer" (2.69s) and small difference for "limited access barrier lane" (3.17s) compared to base scenario (3.24s)	Driving simulator
Rahmati et al.	2019	HDV drivers felt more confident following a CAV compared to another HDV resulting in shorter following distance when driving behind an CAV	Field test
Zhao et al.	2020	1. Differences are found in following-behavior of HDV drivers behind a HDV compared to CAV in terms of THW and standard deviation of speed. 2. Differences potentially explained by subjective trust in automated driving technologies	Field test
Mahdinia et al.	2021	1. On average, a HDV driver who follows an AV shows lower driving volatility in terms of speed and acceleration. On average 23.5% reduction 2. Lower speed variances between leading AV and following HDV. Reduction of 18.8%	Field test
Lateral driving behavior			
S. Lee and Oh	2017	Increased penetration rates of AVs lead to longer lane change duration and higher acceleration noise	Driving simulator
S. Lee et al.	2018	1. Increased penetration rates of AV lead to longer lane change preparation duration of HDV driver 2. HDV driver exhibits more radical driving behavior when trying to change lane into a vehicle platoon 3. Average speed, gender, age and AV penetration rate affect likelihood of lane change failure of HDV	Driving simulator
X. Guo et al.	2020	1. For small THW (0.8s) of AV HDV drivers postpone necessary lane change. For THW of (1.1s) and (1.4s) this effect was minimized 3. More radical lane-change behavior was observed in terms of lateral positioning, speed and acceleration	Driving simulator

2.5 Conceptual framework

The findings from the literature are combined in a conceptual model to visualize the focus of this research and dependencies between the different components. Figure 2.4 represents the conceptualization of this research. The conceptual model gives insight in the dynamics of mixed traffic in combination with a VSL system with a focus on driving behavior. For both CAVs and HDVs the context affects the driving behavior. Context variables are type of road, number of lanes, the presence of other road users, type of vehicle and the penetration rate of CAVs. In addition, both type of vehicles are affected by their characteristics. For the human drivers the behavior is affected by their demographic parameters, driving experience, handicaps and preferred driving style. The autonomous driving is determined by the automation characteristics in terms of speed compliance and driving style.

As part of the ITS an VSL is in place with the goal to influence the behavior of human drivers and control the behavior of CAVs. Equal to the fixed speed limit is it assumed that CAV comply 100% with the VSL. For human drivers the speed compliance is heterogeneous as stated in subsection 2.3.4. A VSL can be defined by the speed strategy in terms of speed limit (profile), the number of gantries (spacing) and the credibility of the speed limit which is subjective for all human drivers.

The two main aspects of the model are the CAV and HDV drivers behaviors. It is expected that human drivers change their driving behavior due to the presence of new driving behavior introduced by CAVs. The question is how human drivers adapt their driving behavior. The interaction between the two vehicles determine the aggregated traffic variables flow and safety.

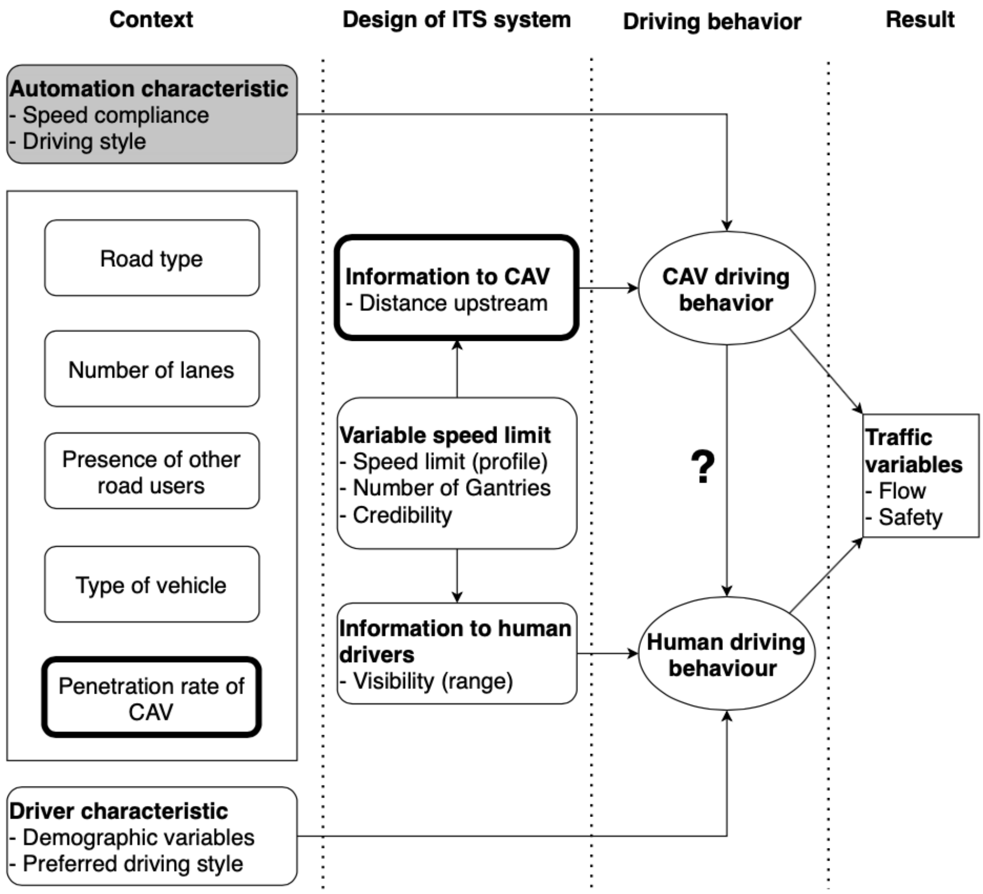


Figure 2.4: Conceptual model

2.6 Hypothesis formulation

Based on literature, hypotheses are formulated for the different research questions. With increased penetration rates of CAVs and upstream speed limit information to CAVs a new traffic situation is created where drivers of HDVs might adapt their driving behavior. On the one hand, drivers are forced to change their driving behavior because of the new traffic context. In the new context with more CAVs a greater share of vehicles will comply with the speed limit. This constrains surrounding traffic in congested traffic situations to drive above the speed limit since the speed of traffic flow is lower. On the other hand, drivers could show different driving behavior because they adapt their behavior to the new driving context. The effects of three factors are researched. The independent variables in this research are, penetration rate of CAVs, upstream information to surrounding traffic and the driving style of the driver. The behavioral adaptation can lead to changes in the longitudinal and lateral driving behavior which are the dependent variables. The dependent variables are characterized by different indicators which are presented below, and the expected effects are summarized in Table 2.2.

Penetration rate (10% and 40%)

A number of HDV drivers may subconsciously mirror behavior of CAVs following the contagion theory of (Connolly & Åberg, 1993). As a result, part of the HDV drivers copy the speed and THW choice of CAVs. In this research, the CAVs are programmed to have a higher speed compliance and keep slightly larger THWs than conventional drivers. Besides, CAVs keep a more constant speed because the preferred speed is fixed. Therefor, it is expected that HDV drivers will comply better with the posted speed limit and keep a larger THW with increased penetration rate of CAV. For both levels (10% and 40%) the same effect is expected. With a higher penetration rate the magnitude of the effects is expected to be higher as well.

Sharing the speed limit upstream to CAV (600m and 900m)

From previous research regarding speed compliance with VSL it is found that speed compliance is higher when slower leading vehicles are present and when drivers start to adapt their speed earlier (Varotto, Jansen, Bijleveld, & van Nes, 2021a). With upstream information to CAVs some vehicles will start to adapt their speed more upstream compared to conventional traffic under VSL. Following the contagion theory, HDV drivers are expected to mirror the speed strategy. If the speed limit is presented more upstream to CAVs then HDV drivers are expected to lower their speed more upstream resulting a lower average speed and a higher speed compliance. Upstream information will lead to a more gradual deceleration profile with less sudden breaking actions. This could increase the THW because following the leading vehicles becomes easier.

However, the potential information asymmetry between CAVs and HDVs drivers could lead to misunderstanding and frustration of drivers of the HDVs. HDV drivers could feel blocked by decelerating traffic when the reason for the speed reduction is unclear to them. Following the psychological frustration-aggression hypothesis, frustration could lead to aggressive driving behavior of frustrated drivers (Dollard, Doob, Miller, Mowrer, & Sears, 1939). It is expected that more lane changes are made and with a more aggressive character, resulting in a decrease of lane change duration and more lane changes.

For both levels (600m and 900m) the same effect is expected. Similar to the penetration rate, the magnitude of the expected effect is positively correlated with the distance.

Driving style of human drivers (social and aggressive)

Since human drivers have a heterogeneous driving style, it is expected that human drivers react differently to an increased penetration rate and upstream speed limit information to CAVs. The driving style of human drivers can be expressed on a social/aggressive driving style scale. A more aggressive driving style can be observed by more lane changes and shorter lane change duration (Johnson & McKnight, 2009). Besides, it is expected that speed compliance is negatively correlated with an aggressive driving style. Moreover, more aggressive drivers are expected to keep a shorter THW.

Table 2.2: Hypothesis summary, (-) indicates that no hypothesis is formulated

	Researched effect:		**Penetration rate (%)**	**Upstream info (m)**	**Driving style**
	Researched levels:		10% and 40%	600 and 900	Aggressive
	In comparison with:		0%	300	Social
Behavior	**Indicator**	**Ref.**	**H.1**	**H.2**	**H.3**
Longitu-dional	Mean speed	**1**	Decrease	Decrease	Increase
	Section entry speed	**2**	Decrease	Decrease	Increase
	Speed compliance[1]	**3**	Increase	Increase	Decrease
	Time headway	**4**	Increase	Increase	Decrease
Lateral	Number of lane change	**5**	-	Increase	Increase
	Duration of lane change	**6**	-	-	Decrease

In order to test the hypothesis, a driving simulator experiment is set up. The research methodology is presented in the next chapter.

[1]Speed compliant is defined as driving below 110% of the posted speed limit

3. Research methodology

This research builds on two stages. In the first stage, a literature study is executed to review the state of the art regarding mixed traffic, behavioral adaptation in mixed traffic and VSL systems. The insights from the literature study are used in two ways. First, the literature study is used to identify the research gap presented in section 1.2. Second of all, the insights from literature form the basis for the setup of the driving simulator experiment in terms of road environment and driving behaviors. The second stage consists out of a driving simulator experiment. The driving simulator experiment is used to give answer to research questions 1, 2, and 3. This chapter gives background information on driving simulators, states the equipment used in the experiments, and presents the experimental design. An overview of the methodology is presented in Figure 3.1.

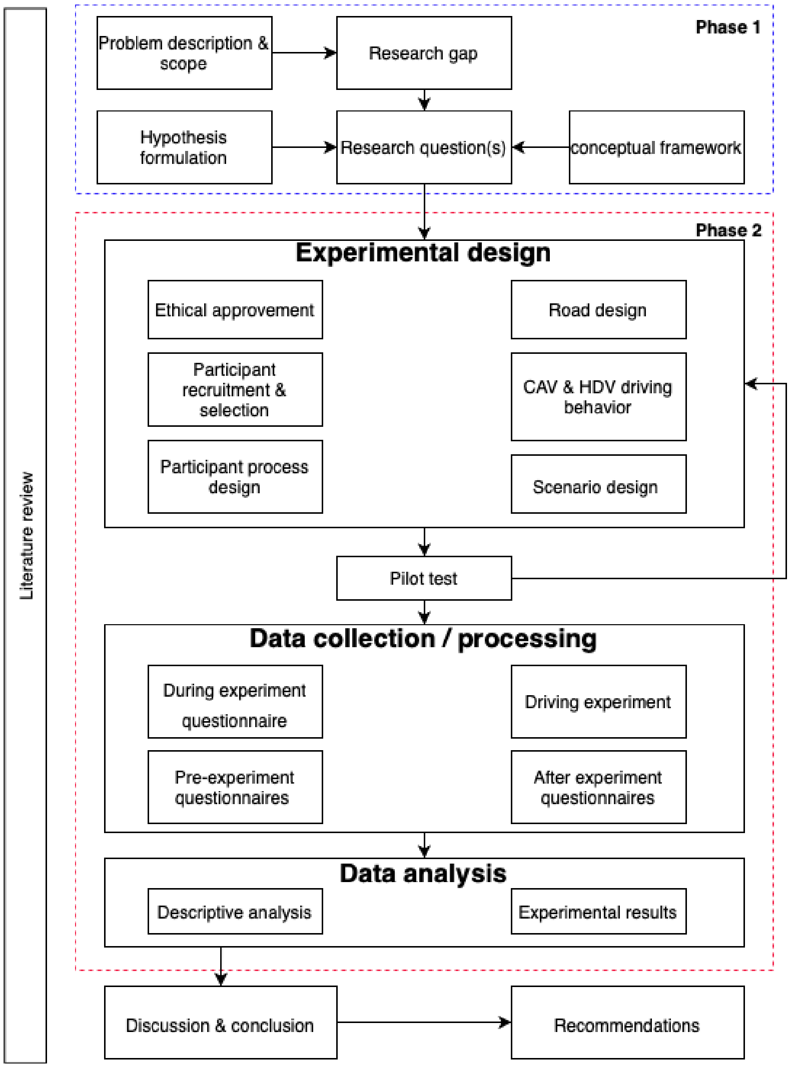


Figure 3.1: Overview of methodology

3.1 Driving simulator background

In transportation there are three commonly used methods to collect information on driving behavior. The methods differ in type and quality of data and have their own constraints and benefits. The three types are: questionnaires, naturalistic driving and driving simulators. Stated preferences questionnaires results in subjective answers of participants and tend to bias the results (Fifer, Rose, & Greaves, 2014). Contrary, naturalistic driving experiments lead to objective study data due to actual observed driving behavior in a real-life context. However, naturalistic driving studies are often expensive, impractical and not capable of testing due to not yet implemented innovation or technologies (van Huysduynen, Terken, & Eggen, 2018). The third method is a driving simulator. Using driving simulators is a popular method for studying driving performance and driving behavior studies in transportation research (Carsten & Jamson, 2011). A driving simulator is a laboratory tool consisting of at least a screen to display an environment, vehicle controls, auditory signals and a dashboard. Driving simulators can be classified in three levels, high-end, mid-level and low-end. A driving simulator is a popular method for numerous reasons. The greatest motivation to use a driving simulator is the efficiency and effectiveness. The ability to control the experiments in terms of participants, scenarios, repeatable situations and scenes in a driving simulator is very high. Scenarios that can not be tested in real traffic situations due to safety issues, not yet implemented technical solutions or rare events can be researched in driving simulators. Moreover, a driving simulator can collect a lot of data on the vehicle used and its environment. Furthermore, by controlling the experiment, the randomness in the data is decreased significantly compared to real-world observations (Carsten & Jamson, 2011). Aspects to take in mind when executing a driving simulator study are validity and simulator sickness.

3.2 Driving simulator equipment

The driving simulator software used for this research is the SCANeR (v1.9) by AV Simulation. The simulator is built up from a fixed-base seating with three 4K high resolution screens providing participants a 180-degrees vision, in combination with a Fanatec steering wheel and pedals. This type of setup can be categorized as a mid-level simulator. The simulator is able to simulate many environments and designs and is able to include technologies as connected and automated driving and VMS in the experimental designs. The simulator is located at the faculty of Civil Engineering and Geosciences at the Technical University of Delft. An image of the driving simulator is included in Figure 3.2.

Figure 3.2: Image of driving simulator

3.3 Experimental design

In this section the experimental design is set out regarding the road design, driving behavior, scenario design, data analysis method and the participant recruitment.

3.3.1 Road design

The road environment where this research focuses on is a motorway segment installed with an VSL system with the goal to warn upstream traffic on congestion and on lower speeds downstream and to prevent crashes on traffic jam tails, the so-called Congestion Warning System. The Congestion Warning system is the most common application of the VSL in the Netherlands (Beemster, Wilmink, & Taale, 2017). A decreasing speed limit strategy from 100 to 70 and finally to 50 is applied. At the first VMS a text messages is added to communicate the reason for the speed limit reduction in order to increase the credibility of the VSL system. A three-lane road section is used because this is a common road environment in the Netherlands and to give the participants the ability to execute their own lane and speed strategies. Both HDVs and CAVs are part of the mixed traffic environment presented to the participant, whereas in the base scenario only HDVs are present. The test/subject vehicle is a HDV as specified in section 1.4. The CAVs are not recognizable to prevent participants from adapting their driving style based on knowledge on mixture of type of vehicles in their surrounding. A visual overview of the road section is presented in Figure 3.3. The expected driving time including the on- and off-ramp is 4-5 minutes depending on the driving style of the participant.

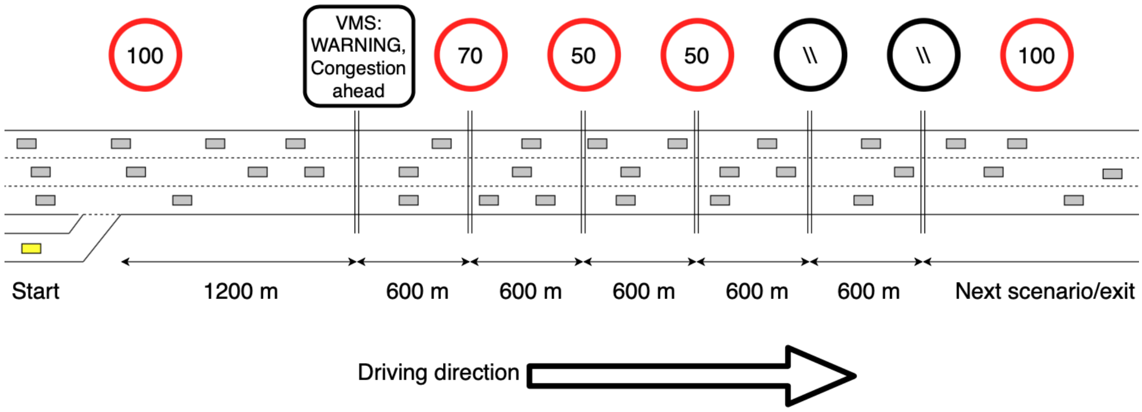
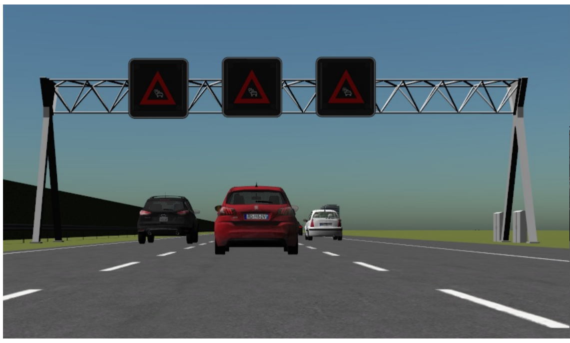


Figure 3.3: Road section

Implementation of road design

To prevent participants to be distracted from traffic from the opposite direction, a single direction motorway was established. Throughout the road sections, bushes and trees were placed on the left side of the road to block their sight to the opposite direction. Next to the parking place, extra bushes are placed between the main road and the parking place. This is done to prevent participants to see other traffic starting up and accelerating once a run is started. To provide some visual distraction a herd of cows was placed at the right end of the parking place. The Dutch VSL signs were imported from a free database named 3DWarehouse. With a free available software tool SketchUp the signs were adjusted to satisfy the needs for the driving simulator. The signs were added as static objects which resulted in a reduced visibility of the signs to real-life. To increase the visibility the signs were enlarged by 150%. At this ratio the signs were still perceived as realistic. Because the signs could only be added as static objects no flashing lights were active on the signs. The different signs are presented in Figure 3.4



(a) Warning message

(b) Speed limit 70

(c) Speed limit 50

(d) End speed reduction

Figure 3.4: Variable message and speed signs

3.3.2 Driving behavior

Next, the driving behavior of the two vehicle types needs to be specified in a way to represent real-world driving behavior. The driving behavior set up is based on car-following, lane changing and speed compliance behavior. The car-following and speed compliance behaviors differ per vehicle type, per human driver and per preferred automation setting. Lane changing behavior is similar for both types of vehicles. The lane-changing behavior for HDVs and CAVs are modeled in the same way for the reason that CAVs only make use of ACC which means that drivers are still responsible for the lateral driving task. A detailed description per vehicle type is described below and an overview of the driving styles is presented in table 3.1 below.

Human Driven Vehicle

Car-following of HDVs is specified by the preferred THW of the driver. Since every driver has his/her own preferred THW, it can best be described by a distribution. In this research, a truncated log normal distribution is used. It must be taken into account that differences are present between THWs observed in empirical studies (average THW: 1.2s (Brackstone et al., 2009; Loulizi et al., 2019)) versus THWs observed in driving simulators (average THW: 3s (Ali, Sharma, Haque, Zheng, & Saifuzzaman, 2020; Schoenmakers et al., 2021). Because human drivers are not able to keep a constant THW the preferred THW is updated every 5s to represent the unstable and random car-following behavior of human drivers.

A normal speed compliance model is used to simulate speed compliance in a VSL scenario. Dutch motorway speed statistics of Rijkswaterstaat form the basis for the speed compliance model (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2020). On average 50% of drivers exceed the speed limit. The standard deviation of the speed violation is found to be 13.7 kmph at a speed limit of 100 kmph on a motorway. It is assumed that HDV drivers show the same speed compliance for decreased speed limits on motorways. The preferred speed of HDV drivers is randomly drawn from a normal distribution and kept relatively constant related to the posted speed limit. This entails that drivers who prefer to speed at speed limits of 100 kmph also speed at lower speed limits. Boundaries (20% of speed limit) are set to the preferred speed to prevent that some vehicles drive very slow or fast.

As discussed in subsection 2.3.4 the speed compliance of human drivers at the first few VSL signs is commonly lower due to the inability to decelerate quickly. The speed adaptation behavior of human drivers approaching VSL systems differentiates in terms of breaking point and breaking intensity (Matowicki & Pribyl, 2021). The first drivers start to reduce their speed from 300m in upstream of the signs, and others only start deceleration at or even after the VSL sign (Matowicki & Pribyl, 2021). A uniform distribution between [300, -50] is applied to the starting point of breaking/decelerating actions of HDV drivers acting on a lowered speed limit shown by a VSL. A smoothing time of 20s is adapted to simulate the inability of human drivers to quickly and firmly react to new speed limits. As a result, it takes HDV 20s (in free flowing traffic) to drive at their preferred speed after passing a reduced speed limit.

Connected and Automated Vehicle

Car-following behavior of CAVs is regulated by the automation setup regarding preferred THW set by the human driver. This means that at CAV follows leading vehicles at a constant THW unless the leading car is exceeding the preferred speed of the CAV. Different THW settings are available for drivers using ACC. Most drivers choose a THW between 1s - 2.2s with the majority on the lower side (Alkim, Bootsma, & Hoogendoorn, 2007). It is assumed that once a THW setting is chosen this is a fixed parameter and is not changed for varying traffic conditions.

The speed compliance behavior for CAVs with information on the speed limit is assumed to be 100% compliant. This results in vehicles driving exactly at the speed limit in case of free-flowing traffic conditions. In case of arriving at a reduced speed limit, CAVs reduce their speed gradually before it arrives at the new speed limit. In this research the two distances upstream are chosen from which the CAVs start to adapt their speed. The speed is gradually lowered by a constant deceleration to have smooth deceleration and prevent unnecessary hard breaking actions.

Lane-changing and lane distribution

The lane-changing behavior of vehicles is incorporated in the driving model in the software package of AVsimulation. In the standard lane-changing model all vehicles have a strong preference to drive on the most right lane. Moreover, lane-changes to faster (left) lanes are rare. At a high volume (congested situation) this results in a slow driving traffic jam on the right lane with the other lanes being unused. In order to test the driving behavior in realistic traffic situations the lane-changing model is mechanically adjusted. First, a parameter is added to prevent 70% of traffic from changing a lane. This parameter is updated every 15s to introduce randomness in the vehicles selected not allowed to change lane. Second of all, invisible triggers are placed on the road to activate a lane change to induce lane-changes made to the more middle and left lane. These triggers are placed on the right and middle lane, placed 250m apart per lane. At these trigger points 10% of traffic is activated to make a lane changes when the gap on the goal lane is sufficient. As a result, the lane distribution is balanced between the three lanes and a normal amount of lane-changes are observed in a congested traffic situation.

Table 3.1: Driving behavior parameter setup for HDV and CAV

	Car-following		Lane-changing	Speed compliance	
	THW Distribution (s)	*(De)-acceleration rate (m/s^2)*	*Overtake risk factor*	*Speed (kmph)*	*Reaction distance to VSL (m)*
HDV	Truncated normal, min: 0.6, max: 2.1, mean: 1.5, sigma: 0.4	Default	Default	Speed limit, SD: 0.137 * speed limit	Distr. uniform 300 to -50
CAV	Triangular, min: 1.0, max: 2.2, mode: 1.6	Default	Default	Equal to speed limit	Scenario dependent

3.3.3 Scenario design

The scenarios are build up from two input variables. *Penetration rate of CAV* of the total traffic on the road and *distance* of information provision on upcoming speed limit to CAV. The levels per variable can be found in the table 3.2. The scenarios do not differ in terms of physical environment as buildings, guardrails, trees etc. The levels of penetration rate are based on predictions for penetration rate of AVs by Milakis et al. (2017) for 2030 and 2050. Although great uncertainty exist on the penetration rate and the level of automation, these two levels are chosen to represent the near future (2030) and far future (2050). The distances for upstream information are based on the current design distance between gantries in the Netherlands (600m), an extreme case (900m) and the base case of 300m which is the first distance at which HDV drivers start to adapt their speed when approaching a VSL, see subsection 2.3.4.

Table 3.2: Input variable levels

Variable	Base	Low	High
Penetration rate CAV (%)	0	10	40
Distance (meter)	300	600	900

Only the penetration levels of 10 and 40 percent are combined with a level of distance upstream, since it is impossible that information is presented upstream in case there are no CAVs present. In case of no prior information, it is assumed that CAVs respond at a distance of 300m towards upcoming changing speed limits. The value of 300m is chosen because it is the first distance at which conventional drivers start to adapt their speed. This results in a total of seven scenarios, as presented in Table 3.3 below. A repeated measures design is chosen. Participants drive each scenario two times to increase the observations per scenario and be able to check for learning effects. Moreover, the order of the scenarios is randomized between participants to counterbalance order effects.

Table 3.3: Description of scenario and independent variable level combination

Scenario number	**Penetration rate CAV (%)**	**Distance[1] (m)**
1	0	-
2	10	300
3	40	300
4	10	600
5	10	900
6	40	600
7	40	900

3.3.4 Driving behavior indicators

To analyse the driving behavior of the participants in driving simulator a selection of performance indicators are used. The indicators of interest are listed per driving behavior type in Table 3.4 below.

Table 3.4: Driving behavior and corresponding indicators

Driving behavior	Performance indicators
Longitudinal	Speed (kmph), mean and distribution Section entry speed (kmph) Speed compliance (s), time above 110% of the speed limit Time headway (s), mean and distribution
Lateral	Number of lane changes (#) Duration of lane change (s)

These indicators are chosen because the fundamental driving behavior of participants is of interest. The indicators represent the driving behavior of participants well and are relatively easy to interpret. Moreover, only a limited number of indicators can be examined due to the time constraint of this research. Next to the stated indicators above, the indicators speed and THW are analyzed relative to the distance and different road segments. The profiles are analyzed to compare the effects of the different scenarios on specific locations. The indicators will be discussed in dept in section 4.2.

3.3.5 Survey design

Furthermore, surveys are being used to collect data on demographics, experience, trust, knowledge and meaningfulness regarding automation and VSL systems. This data is used to see if significant correlations are present between driver characteristics and driving behavior. The surveys are conducted on three different moments, pre-, during- and after-experiment. In the subsections below the surveys are introduced. The survey questions are presented in Appendix B.

Pre-experiment

First, participants are asked to provide information on their demographics (e.g. gender, date of birth, level of education, driving experience).

Second, participants are asked to self-asses their driving style. Two commonly used surveys are the Driving Behavior Questionnaire (DBQ) (Reason, Manstead, Stradling, Baxter, & Campbell, 1990) and the Multidimensional Driving Style Inventory (MDSI) (Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). The DBQ relates to the errors and violations that contribute to unsafe driving behavior, and the MDSI uses eight factors to represent a driving style. However, for this research an alternative method is chosen, the Pro-social and Aggressive Driving Inventory (PADI) (Harris et al., 2014). The PADI gives insight into two subcategories of driving style, pro-social and aggressive. No specific insights in the constructs behind the driving behavior is needed in this research and just a scale to classify the driving style of the participants is sufficient the PADI is best to use. Besides, the classification of a driving style on a range of social to aggressive is of special interest since a positive correlation is expected between a social driving style and a higher speed compliance, see section 2.6.

Third, participants are asked to state their experience with both ACC and VSL systems. The survey reviews the participant's experience on two different sub constructs, usefulness and satisfaction. If participants perceive systems in place as useful, the compliance with

[1] Distance upstream where the reference point is the location of the gantry with the VSL

the system is expected to be higher (Matowicki & Pribyl, 2021). Furthermore, studies showed the relation between perceived meaningfulness of information and the attention for the information. If humans perceive information as meaningful, they tend to give more attention to it (Desimone & Duncan, 1995). A questionnaire from (Van Der Laan, Heino, & De Waard, 1997) is used to measure the acceptance towards both ACC and VSL.

The list of questionnaires combined in the pre-experiment survey are:

1. Demographic questionnaire
2. Pro-social and Aggressive Driving Inventory
3. Acceptance questionnaire

During-experiment

After each scenario a survey is used to observe the experience of the participant in a specific scenario. The questions asked relate to the perceived workload, stress, frustration etc. The insights of this survey are used to compare the scenarios based on the subjective driving experience of the participants. The questions in the experience questionnaire designed specifically for this study.

The questionnaire included in the during-experiment survey is:

1. Experience questionnaire.

Post-experiment

After the driving experiment two last questionnaires are conducted. The first survey is a simulator sickness questionnaire to investigate whether the results are potentially influenced by a state of discomfort of the participant, which would mean that the results are invalid. An existing survey is adopted from Kennedy, Lane, Berbaum & Lilienthal (1993).

The second questionnaire relates to the participant's perceived presence in the virtual environment. The perceived presence give insight to what extent the participant was involved in the driving experiment. This survey is used to identify participants with potential invalid results due to zero to little involvement or extreme involvement of participants in the virtual environment. Again, an already established survey is used by Witmer & Singer (1998).

The list of questionnaires included in the post-experiment survey is:

1. Presence in the virtual environment questionnaire.
2. Simulator sickness questionnaire.

3.3.6 Participant recruitment, selection and process

All humans are prone to behavioral adaptation. Therefore, the effect is researched on the overall population, which means that a representative group of participants needs to be selected from all different age groups and gender. A prerequisite is a driving license. No familiarity is needed with either CAV or VSL.

The recruitment of participants is done by advertisement in a newspaper, advertisement on the university campus by posters at the faculty and by advertisement via social media.

Sample size

The population in this case consists out of all Dutch inhabitants with a valid driving license, which is around 11.4 million people in 2021. Multiple strategies exist to determine the right sample size to be representative for the population. The basis formula to determine the right sample size in case of big population is presented in Equation 3.1 below (Cochran, 1963):

$$n_0 = \frac{Z^2pq}{e^2} \tag{3.1}$$

where,
Z = The z-score corresponding to a specific confidence interval
p = The estimated proportion of an attribute that is present in the population
$q = 1 - p$
e = The desired level of precision

Generally, a significance level of 95% is used in behavioral science. The corresponding z-score is 1.96. The variability in the population in this research is expected to be small and therefor a p-value of 0.1 is chosen. The desired level of precision is set to 0.1. This results in a sample size of 35.

Another accepted approach to determine the sample is to use the same sample size as similar studies do (Israel, 1992). A typical sample size for studying behavioral adaptation in mixed traffic is 20-40 participants (S. Lee et al., 2018; Gouy et al., 2014; Schoenmakers et al., 2021; Naujoks & Totzke, 2014). The reason for the small samples sizes is the time-consuming aspect of conducting a driving simulator experiment. The previously found sample size of 35 is a sufficient sample compared to similar studies.

Participant process

In the first step of the process, participants were asked to fill in three online surveys, at least three days prior to the driving experiment, concerning their demographic characteristics, their driving style and their attitude towards VSL and CACC. Besides, participants were asked to read an information sheet (see Appendix C) and sign their consent declaring that they voluntarily participate in the experiment and have the right to withdraw at any given moment. The research has been approved by the ethical committee of TU Delft. At the day of the driving experiment, participants were briefed on the driving simulator proceedings and the hypothetical goal of their drives (for pre-experiment briefing, see Appendix D). After each scenario the participant is requested to fill in a survey on their experience with that specific scenario. When all scenarios are finished the participants are provided with a last survey containing the simulator sickness questionnaire and the presence in the virtual environment questionnaire.

All documents were provided in both English and Dutch language versions.

4. Data collection and processing

In this chapter the process is explained which is used to collect and process the data from both the questionnaires and the driving simulator. Both data sources result in raw data files which needs to be processed before they can be analyzed. First, the different road sections as defined in the experimental road design are described and the specific research area of interest is defined. Second, the driving indicators are defined. Last, the method of data processing of the different surveys and driving simulator is explained, as well as the software used for this data processing.

4.1 Road design sections

In order to analyze the driving behavior, the road section is divided over different road sections. In this way the behavior can be compared within and between participants at different stages of the speed reduction strategy. The different road sections are presented in Figure 4.1 and described in detail below.

4.1.1 Detailed section description

The different road sections are described based on their geographical location and information on specific traffic rules presented.

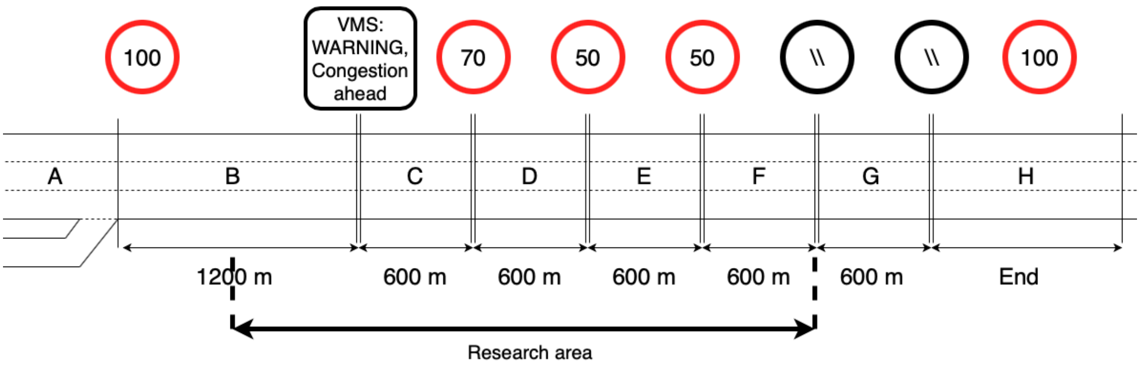


Figure 4.1: Road section including research area of interest

A: Start

In section A the participant starts the scenario. The participant's vehicle is parked at a motorway rest area. section A also includes the on-ramp to the motorway. In section A the goal of the participant is to accelerate to a sufficient speed to enter the motorway. The maximum speed at the motorway in section A is 100 kmph.

B: Warm-up

The goal of the participants in section B is to further accelerate to their preferred speed on a road section with a posted speed limit of 100 kmph. At the end of section B a VMS is installed showing a triangular road sign warning for congestion downstream. In the analysis section the warm-up section is abbreviated with WA.

C: Approach

section C covers the road section between the warning sign and the first VSL. In section C the legal speed limit is still 100 kmph. All following sections between two VSL have a total length of 600 meters. In the analysis section the approach section is abbreviated with AP.

D: 70

At the start of section D the posted (and legal) speed limit reduces from 100 kmph to 70 kmph. This is an intermediate speed used by Dutch road authorities to slow down traffic in a congested situation.

E: 50-1

At the start of section D the posted (and legal) speed limit reduces from 70 kmph to 50 kmph. 50 kmph is the lowest posted speed used on VSL signs by road authorities in the Netherlands.

F: 50-2

In section F the speed limit 50 kmph of section E is repeated. The legal speed limit of 50 kmph is valid for the whole section and only changes at the location of the next VSL sign.

G: End speed reduction

After passing the VSL sign at the start of section G the reduced speed limit is lifted and goes back to the normal speed limit of 100 kmph. Traffic will start to accelerate to the normal speed limit.

H: Normal limit/End

In section H the normal speed limit of 100 kmph is active. After the second VSL stating the reduced speed limit is lifted, the scenario is ended.

4.1.2 Research area description

The road sections of interest are the sections where drivers could show potential changes in driving behavior due to the VSL and CAV. Participants need a bit of distance to join the motorway from the on-ramp and get to their normal driving style in terms of lane, speed and THW according to the traffic situation. The start of the research area is set to 600m after the on-ramp. The following section is the second half of the warm-up section. From here on the warm-up section is defined as the second half of the original 1200m long warm-up section. The first distance at which a CAV receives information on the upcoming speed limit is at 900m (for scenarios 5 and 7). This results in CAVs adapting their current speed at a distance of 900 from the on-ramp i.e. halfway into the warm-up section for those the scenarios with a large distance of upstream information. The end of the area of interest is after the last 50 section. In this section it is expected that some drivers will still be reducing their speed to the speed limit of 50kmph. After this section the speed limit increases back to the normal speed limit of 100kmph. The accelerating behavior is not of interest for this research and thus this is the last section that is analyzed.

4.2 Definition of driving behavior indicators

In order to analyze the driving behavior, the indicators need to be defined. When possible, previous literature or reports are used to define the indicators. The report of the Society of Automotive Engineers (2015) is used as a leading document.

Mean speed

The mean speed is the average speed of the subject vehicle on a specific road stretch. The mean speed is an indicator of the efficiency of the traffic flow.

Section entry speed

The section entry speed is the speed of participants at the location where they pass the VSL sign. This location is of interest because this is the location where legally the speed limit changes in case a reduced or increased speed is displayed.

Speed compliance

The time above the speed limit and the magnitude of the speed violation are both of interest, since both crash risk and crash severity increase with higher speeds (Aarts & van Schagen, 2006). The speed compliance can be defined by the time above a certain threshold (fixed or relative to the speed limit). In literature and other research the threshold is defined in various ways. Because the road section contains different speed limits a relative threshold makes more sense. In this research a threshold of 110% of the speed limit is used. In the data analysis the time spend speeding is used to indicate the speed compliance. A decrease in speeding time means a higher speed compliance.

Time headway

The THW is defined in the HCM as "the time between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper)" (TRB, 2010, p. 9-9). Following behavior is defined as driving behind a leading vehicle at less than 6s THW. Therefore, only THWs below 6s are taken into account. In the Netherlands drivers are advised to keep a minimum THW of 2 seconds (Risto & Martens, 2013).

Number of lane changes

A lane change is defined as "lateral movement of a vehicle from one lane of a traveled way to another lane on the same traveled way with continuing travel in the same direction in the new lane" (TRB, 2010). Only discretionary lane changes are of interest, which means that merging from on-ramps and merging to exits are not taken into account in this research.

Duration of lane changes

To determine the duration of a lane change the beginning and ending of a lane change need to be specified. Different ways exist from eye-tracking, using the turn signals and physically crossing a lane boundary. Because eye-tracking is not possible and turn signals are unreliable (not always used) the most objective way to define a lane change is by the lateral position of the car on the road. The start of a lane change is when the first front tire of the subject vehicle touches the lane marking, the end is when the last back tire of the subject vehicle crosses the lane marking again (SAE, 2015). The time in between these events is the duration of a lane change. In some cases participants do not complete the lane-change. In these cases the participant crosses the lane marking with their front tire but do not cross it with their back tire. To prevent these cases from disrupting the lane change duration indicator lane changes with a higher duration than 10s are disregarded.TRB, Highway capacity manual 2010, Volumes 1-4.

TRB, Highway capacity manual 2010, Volumes 1TRB, Highway capacity manual 2010, Volumes 1-4.

4.3 Data processing

Before the collected data from both the questionnaires and the driving simulator is analyzed, it needs to be post-processed. The subsections below set out the data processing for the different questionnaires and the driving simulator.

4.3.1 Pre-experiment survey data processing

In the first part of the pre-experiment survey demographic variables are stated. Based on these variables different groups can be made based on personal characteristics as age, gender, education etc. Besides, groups can be made on road usage characteristics as driving experience, weekly motorway usage and the availability of ACC the car of the participant. Moreover, to answer sub-question 4 groups can be made based on participants' self-reported driving style index which is a result of the PADI questionnaire.

The first 17 questions of the PADI survey score the social behavior and the last 12 questions relate to aggressive driving behavior. A 7-point Likert-scale is applied ranging from 'never' to 'always' (coded as 1 to 7) to indicate for question item how often they engage in each of the stated driving behaviors. This results in a maximum social score of 119 and a maximum aggressive score of 84. The driving style index is computed by subtracting the total aggressive score from the total social score. The highest score that can be reached is 107 (119 social - 12 aggressive). The minimum score which represents aggressive driving behavior is -67 (17 social - 84 aggressive).

The experience questionnaire measures two different constructs, the usefulness and satisfaction of a particular technology. The survey consists out of nine questions, see Appendix B. A 5-point Likert scale (coded as -2 to 2) is used to survey different indicators of the two constructs. The usefulness score ranges from -10 to 10 (5 questions) and the pleasantness ranges from -8 to 8 (4 questions).

4.3.2 During-experiment survey data processing

The during-experiment consists out of 5 questions capturing different driving experience concepts regarding their own state of being, "how much mental activity was required (thinking, deciding, calculating, looking, searching, etc. to accomplish your level of performance?", to their experience regarding the traffic situation, "were you able to drive 'freely' or did you feel blocked/held up by surrounding traffic?". A 5-point Likert scale is used to score the concepts. After each run, the data is collected on the experience of the participants. This gives the opportunity to compare both potential differences between different scenarios and potential learning effects for a similar scenario.

4.3.3 After-experiment survey data processing

The simulator sickness survey contains 16 questions regarding different symptoms of physical discomfort as headache, eyestrain, vertigo etc. The symptoms are rated on a 4 point Likert scale ranging from 'none' to 'severe' (coded as 0 to 3) to indicate the magnitude of the symptom. The different symptoms load on one or more sickness constructs (oculomotor, disorientation and nausea). Afterwards, the three constructs are multiplied by specific weights and summed. For a detailed description of the method, loading and weights see Kennedy et al., (1993). The maximum simulator sickness score is 236.

The presence survey measures the involvement of the participants in the scenarios and the virtual environment. 32 questions are established and rated on a 7 point Likert scale (coded as 1 to 7). The total presence is a simple summation of all the scores, which results in a minimum score of 32 and a maximum of 224.

4.3.4 Driving simulator data processing

The simulator saves information on all vehicles at a frequency of 20Hz. To reduce the size of the extracted files the frequency is reduced to 4Hz. A frequency of 4Hz provides enough detail for the above-mentioned indicators to examine the driving behavior. A selection of variables is exported based on the needs for data analysis. An overview of the selected variables extracted from the simulator is presented in Appendix E.

4.3.5 Data processing software

Prior to the experimental analysis, a descriptive analysis is executed to get insights into the characteristics of the sample and mean values regarding the driving indicators. The results are presented in chapter 5 and chapter 6. The software package used to process the data is Anaconda. Within Anaconda, Jupyter is chosen as Integrated Development Environment which uses Python as coding language. To test differences between scenarios statistical analyses are executed. The results of the driving simulator are analyzed using standard statistical analyses with the help of the software package IBM SPSS.

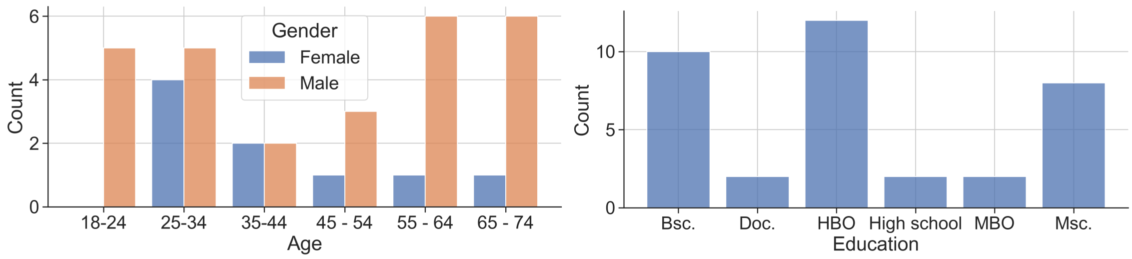
5. Sample and simulator descriptive statistics

In this chapter the sample characteristics and simulator descriptive statistics are presented. First, the sample is described by the results of the pre-experiment survey. Afterwards, the simulator insights are discussed in terms of validity and the potential differences between the two sessions.

5.1 Sample characteristics

A total of 36 participants participated in the experiment. The sample can be described by multiple personal characteristics in terms of demographic information and driving behavior and car-use. The plots below visualize the characteristics and correlations between driving behavior and demographic information and car-use are investigated.

Younger (18-24, 25-,34) and older (55-65, 65-74) age groups are relatively over-represented compared to middle-aged groups, as presented in figure Figure 5.1a. This is probably a result of the recruitment via the (social) network of the researcher. Moreover, time slots being only available during office hours could have contributed to this over representation as well. The overall education level of the sample, visualized in Figure 5.1b, is high, which can be explained by the recruitment as stated before and potentially the correlation between people's interest in innovation/technology and education level.

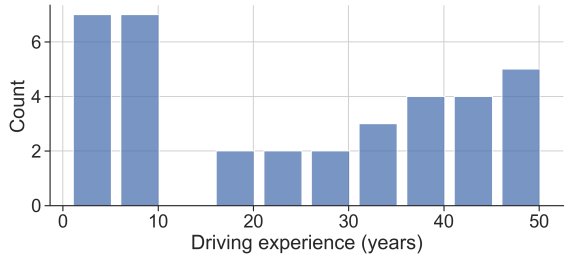


(a) Age and Gender

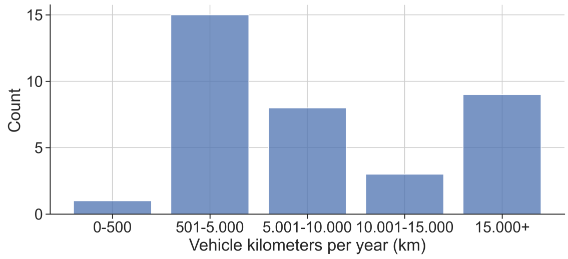
(b) Level of education

Figure 5.1: Demographics

The driving experience (see Figure 5.2a is positively correlated with the age of the participants. As a result, a higher number of participants are on the lower and higher side of the driving experience spectrum compared to the average experience. The amount of kilometers driven on a yearly basis differs greatly with the majority driving 501-5000 kilometers per year and the second group driving 15,000+, which can be seen in Figure 5.2b This suggests that the participants have different driving patterns.



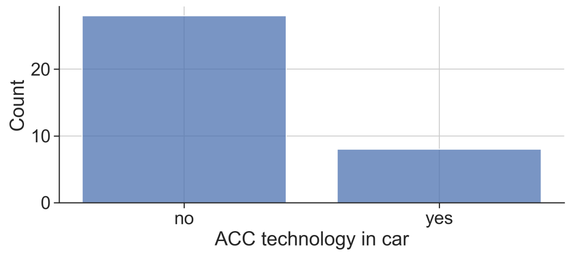
(a) Driving experience



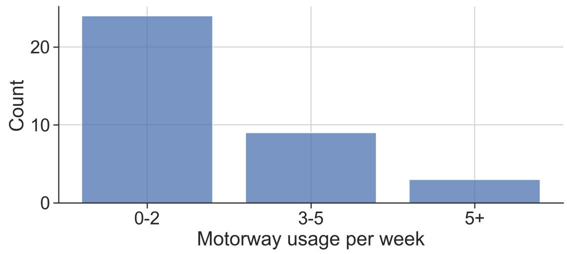
(b) Driving kilometers

Figure 5.2: Driving experience

The car-use can be divided over two interesting indicators related to the technologies investigated in this research. First, the availability of ACC is surveyed (see Figure 5.3a. The presence of this technology could affect the opinion of a participant towards the technology. Second, the motorway usage is of interest because this gives insight in the participant's experience or encounters with VSL systems (see Figure 5.3b. As can be seen in figure Figure 5.3b the majority of the participants do not use the motorway on a regular basis.



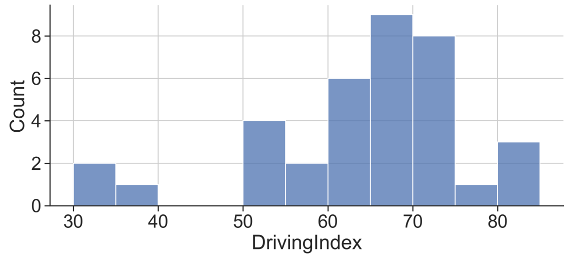
(a) ACC availability



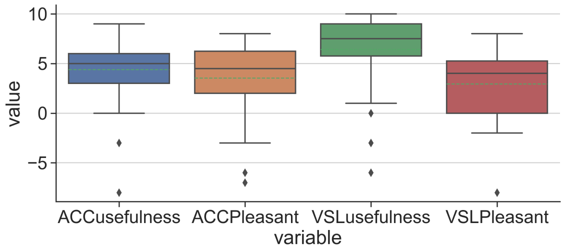
(b) Motorway usage

Figure 5.3: Type of driving

As stated in subsection 4.3.1 the driving index is computed by subtracting the total aggressive score from the total social score for each participant. The aggressive and social scores are statistically significant negatively correlated (-0.32) which means that both scores can be combined into a unified score. A low score on the driving index spectrum represents a more aggressive driving style, a high score represents a more social driving style. The driving index ranges from -67 to 107. Most of the participants score high on the driving index (see Figure 5.4a) which means that most of the participants score themselves as very social drivers. Only three participants score relatively low compared to the others. This could be explained by multiple aspects. It could be that social drivers are more prone to participant in driving simulator experiments where behavior is analyzed. Besides, people are prone to overestimate their own driving skills and behavior compared to other road users. The results are comparable to the results of other researches using the PADI questionnaire (Harris et al., 2014). The driving index has no statistical significant correlations with any of the above-mentioned demographic and car-use variables except for ACC availability. ACC availability is positively (0.34) correlated with a high driving index.



(a) Driving index



(b) Usefulness and pleasantness score

Figure 5.4: Driver characteristics

Participants were asked to report their attitude towards ACC and VSL technologies. Both ACC and VSL score high on their usefulness and pleasantness, see Figure 5.4b. This is underpinned by high correlations between usefulness and pleasantness scores for both ACC (0.73) and VSL (0.69). For ACC the pleasantness and usefulness are rated relatively similar, whereas for VSL the usefulness scores significantly higher compared to the pleasantness. An explanation is that VSL systems are activated during congested traffic condition. On the one hand, the systems functions as a warning for drivers which increases the usefulness. On the other hand, the system reduces the maximum speed limit which can be perceived as unpleasant. The ACC usefulness score does not have a statistical significant correlation with any of above-mentioned variables. The pleasantness score is negatively correlated with education (-0.37) and ACC availability (-0.34). For VSL both the usefulness and pleasantness score have no significant correlations with any of the other variables measured. Considering both systems, the pleasantness score has a larger range between the 25^{th} and 75^{th} percentile. This means drivers score the pleasantness of both systems with a higher variance compared to the usefulness.

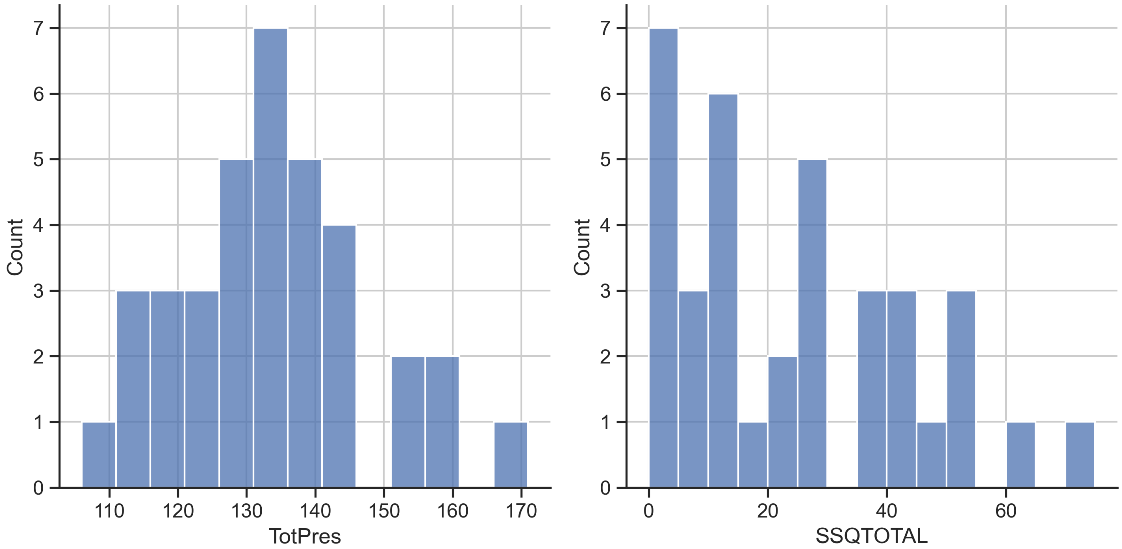
5.2 Simulator insights

In this section the driving simulator and virtual environment are validated with the use of the presence in the virtual environment and simulator sickness scores. Afterwards, the two sessions, before and after the break, are compared to investigate potential differences.

5.2.1 Presence in the virtual environment and simulator sickness scores

The simulator insight in terms of presence in the virtual environment and driving simulator sickness are used to find potential outliers in participants for which the simulator data can not be used. A very low presence score would indicate that the simulator was not perceived as realistic, which means that the observed driving behavior cannot be regarded as realistic driving behavior. For the simulator sickness score high scores need to be disregarded for the reason that symptoms of sickness can mean that the results are influenced by the physical state of the participant.

As can be seen in figure Figure 5.5a the majority of the participants experienced an average (mean: 133.5) presence in the virtual environment (max: 224). None of the participants experienced an extreme low presence as can be seen by the minimum score which is 106.0. All participants scored very low on the simulator sickness score. The highest observed sickness score is 74.8 where the maximum score is 236. The average score is 24.8 which means that the simulator was very safe in terms of physical discomfort. All descriptive statistics for both questionnaires can be found in Table 5.1 Based on both the presence and simulator sickness scores the data from all participants can be used for further data analysis.



(a) Presence in virtual environment (b) Simulator sickness score

Figure 5.5: Simulator characteristics

Table 5.1: Descriptive statistics presence and SSQ

	Presence (224)	SSQ (236)
Mean	133.5	24.8
Std.	14.1	19.8
Min.	106.0	0.0
25%	125.0	7.5
50%	134.0	22.4
75%	140.5	38.3
Max	171.0	74.8

5.2.2 Session insights and comparison

All participants drove each scenario two times. The scenarios were divided over two sessions with a small break (5 - 10 min.) in between. Both sessions contained all seven scenarios and the order was randomized for both sessions. In order to investigate whether differences are present between run 1 and run 2 for the different scenarios statistical test are applied. Only the indicators with continuous observations could be checked for differences with statistical tests.

First, a normality test is executed for both run data sets to see whether a paired sample t-test can be used. The null-hypothesis is that data set x is normally distributed. The confidence interval is set to 95%. For p-values below 0.05 the null hypothesis can be rejected which means the data are not normally distributed in the population. P-values above 0.05 means that the data are normally distributed in the population. Only the data of the first run for indicator Mean THW (see Table 5.2) is found to be normally distributed. Consequently, a normal paired t-test cannot be used for any of the indicators to compare the data of run 1 and 2.

To compare the mean of two related samples which are not normally distributed a Wilcoxon signed-rank test can be used. The test assesses whether the population mean ranks of the two samples differ. The null-hypothesis of the test is that the median of the population differences between the paired data is equal to zero. In case the p-value is smaller than 0.05 the null-hypothesis can be rejected. From Table 5.2 it can be concluded that for all indicators run one does not differ statistically from run two. For that reason run one and run two can be analyzed in the same process. This results in a total of 72 observations per scenario.

Table 5.2: Result statistical mean test run 1 & 2

	Run 1			Run2			Wilc.-test result
	Mean	**Std.**	**Normal**	**Mean**	**Std.**	**Normal**	**P-value**
Mean Speed	66.75	4.76	-	67.38	4.88	-	0.10
Speeding	13.10	13.86	-	15.99	16.22	-	0.15
Mean THW	2.79	0.65	Check	2.66	0.67	-	0.09
Number of LC	2.59	1.84	-	2.74	1.92	-	0.16

6. Experiment descriptive statistics

In this chapter the most important indicators are described and analyzed on a global level for both longitudinal and lateral behavior. Based on the results of the global analysis indicators can be selected to be analyzed in more detail. Only a part of the total road is of interest for the research of the indicators, as visualized in Figure 4.1. The selection starts at a distance of 600m which is 600m after the end of the on-ramp and 600m before the location of the warning sign (WM). The end of the selection is 600m after the first end of the speed reduction sign. The locations of the warning message (WM) and the VSL signs are added as vertical red colored dotted lines in the graphs below. All seven scenarios are visualized in the graphs and plots below, separated by a different color. In the last section of this chapter the indicators are compared for two different groups of participants based on self reported driving style.

6.1 Longitudinal behavior

The speed and THW indicators are selected to be visualized relative to the distance because for these indicators it is most interesting to see potential differences at various distances along the road sections. Next, the averages for the speed and THW are compared for the different road sections and scenarios. The speed and THW profiles are presented in Figure 6.1 and Figure 6.2 below.

A number of simple calculations are executed to reach to the average line of the indicators. For the first step the selected road is divided in blocks of 25m. In the next step the observations for each participant, scenario and run combination are retrieved and averaged for each distance block of 25m. By taking the average block values per scenario and participant a line can be drawn by putting all the block values behind each other. This results in an individual profile for the indicators speed and THW per scenario and participant. Last of all, the individual profiles are aggregated for each scenario by taking the average of all participants and both runs.

6.1.1 Speed

The speed profiles averaged per scenarios are presented in Figure 6.1 below. Based on the speed profiles the speed behavior in terms of mean speed, section entry speed and total time 10% above the speed limit can be calculated.

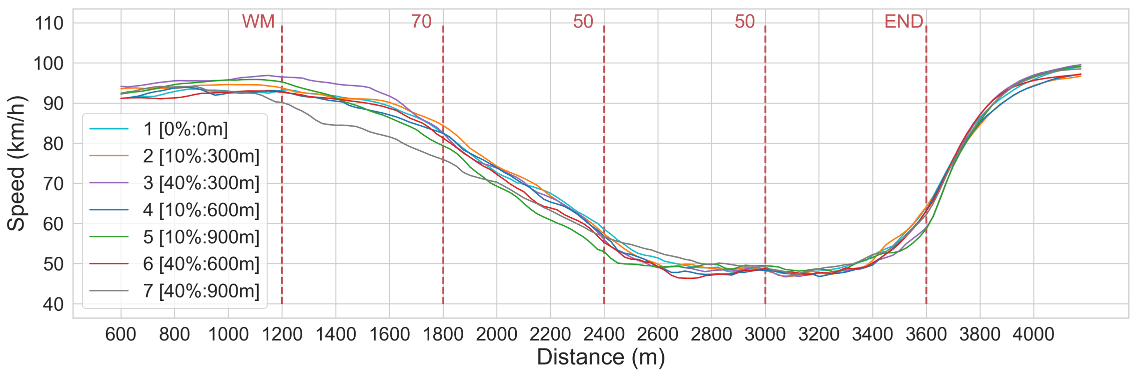


Figure 6.1: Visualization of average speed of all participants per scenario S[P:D] where S: scenario, P: penetration rate, D: distance upstream

In the WA section the scenarios do not differ greatly in terms of speed and no real increase or decrease in speed can be observed. A penetration rate of 40% and no upstream information (scenario 3) results in higher overall speeds in WA and 70 section. This could be an effect of how HDVs and CAVs are modeled. CAVs are programmed to drive exactly at the posted speed limit, whereas HDVs drive at speeds randomly distributed around the posted speed limit. More CAVs means more homogeneous and efficient traffic. This effect is not observed for a penetration rate of 10%. In the AP section participants start to lower their speed. Scenarios 3[40%:300m] (highest) and 7 [40%:900m] (lowest) stand out most in the AP section. In this section the largest differences in speed between the scenarios are present. In the 70 section the deceleration rate is relatively equal for all scenarios visible by the slope of the speed lines. However, the distance where participants reach the posted speed limit of 70 km/h ranges from 2000m to 2150m. This is a result of the different breaking patterns in the previous section. In the middle of 50_1 section the speed profiles tend to converge again. In the following 50_2 section participants start to accelerate at a distance of 3300m, which is at 300m before the end of the speed reduction sign. After the end sign participants keep accelerating until they reach a speed of 100km/h.

From a visual inspection of Figure 6.1 it can be noticed that sections AP, 70 and 50_1 show most interesting differences between the scenarios in case of speed. In order to quantitatively check this the section averages and range between different scenarios are inspected. Table 6.1 presents the section averages. For the speed indicator large differences are present in the AP and 70 sections. Besides, the average speed is almost everywhere below the speed limit with minor exceptions (maximum average speeding of 1.48 km/h in scenario 7 [40%:900m] on section 50_1).

Next to the average speed per section the entrance speed of each section and especially the 70 and 50_1 sections are of interest presented in Table 6.2. Lower entry speeds indicate that drivers start to adapt their speed earlier to the upcoming speed limit. Relative to the mean speed much more speeding occurs at the section entry points. At the 70 section entry the average speeding over all scenarios is 11.24 and at the 50_1 entry the average speeding is 6.17. In contrast, the entry speed at the second 50 section is below the speed limit for all scenarios.

Table 6.1: Mean speed (kmph) per section for all scenarios including scenario average (Av) and range (Ra) per section

	Section				
Scenario	**WA**	**AP**	**70**	**50_1**	**50_2**
1 [0%:0m]	92.09	89.69	69.63	50.17	50.24
2 [10%:300m]	93.92	90.03	70.08	49.70	49.69
3 [40%:300m]	95.24	92.00	69.18	49.42	48.96
4 [10%:600m]	92.31	88.21	69.18	48.79	49.32
5 [10%:900m]	94.46	88.19	64.76	49.17	49.80
6 [40%:600m]	91.79	88.95	67.31	48.37	49.67
7 [40%:900m]	92.63	82.61	65.77	51.48	50.28
Av	93.21	88.56	67.99	49.59	49,71
Ra	3.45	9.39	5.32	2.69	1.32

Table 6.2: Entry speed (kmph) per section for all scenarios including scenario average (Av) and range (Ra) per section

	Section				
Scenario	**WA**	**AP**	**70**	**50_1**	**50_2**
1 [0%:0m]	91.17	93.77	82.56	58.55	48.75
2 [10%:300m]	93.58	93.77	84.42	57.35	48.24
3 [40%:300m]	94.17	96.52	82.58	56.00	48.59
4 [10%:600m]	91.21	92.95	82.48	56.78	48.38
5 [10%:900m]	92.28	95.28	79.38	53.00	49.51
6 [40%:600m]	91.14	92.71	81.31	55.31	48.78
7 [40%:900m]	92.47	90.15	75.94	56.17	49.16
Av	92.29	93.52	81.24	55.88	48.78
Ra	3.03	6.37	8.48	5.55	1.27

6.1.2 Speed compliance

The speeding behavior of participants is described by the time participants exceed the threshold of 110% of the posted speed limit. In Table 6.3 the average time participants speed per section and scenario is presented. The total time participants show speeding behavior per scenario is relatively stable. This indicates that none of the scenarios physically prevents participants from being able to show speeding behavior. The total section values indicate that speeding increases when the speed limit is decreasing.

Table 6.3: Total time speeding +10% (s) including scenario and section totals

	Section					
Scenario	**WA**	**AP**	**70**	**50_1**	**50_2**	**Tot**
1 [0%:0m]	1.1	0.8	8.1	10.2	8.9	29.1
2 [10%:300m]	2.1	1.5	8.8	8.9	8.8	30.1
3 [40%:300m]	2.4	1.3	7.1	8.6	8.3	27.7
4 [10%:600m]	1.5	0.6	7.8	8.4	8.3	26.6
5 [10%:900m]	1.6	0.8	4.9	8.2	8.4	23.9
6 [40%:600m]	0.9	0.9	7.0	8.5	9.2	26.5
7 [40%:900m]	1.6	0.6	5.0	13.3	9.6	30.1
Tot	11.2	6.5	48.7	66.1	61.6	194.0

6.1.3 Time headway

For the THW profile it is harder to observe consistent differences between the scenarios. However, from the warning message to the end sign a slight negative trend can be observed for all scenarios in terms of THW in Figure 6.2. The increase in THW after the end sign could be out of the scope of this research because it is not influenced by upstream information provision. Besides, the drastic increase in THW in this section can be explained by the aggressive acceleration behavior of surrounding vehicles in the driving simulator.

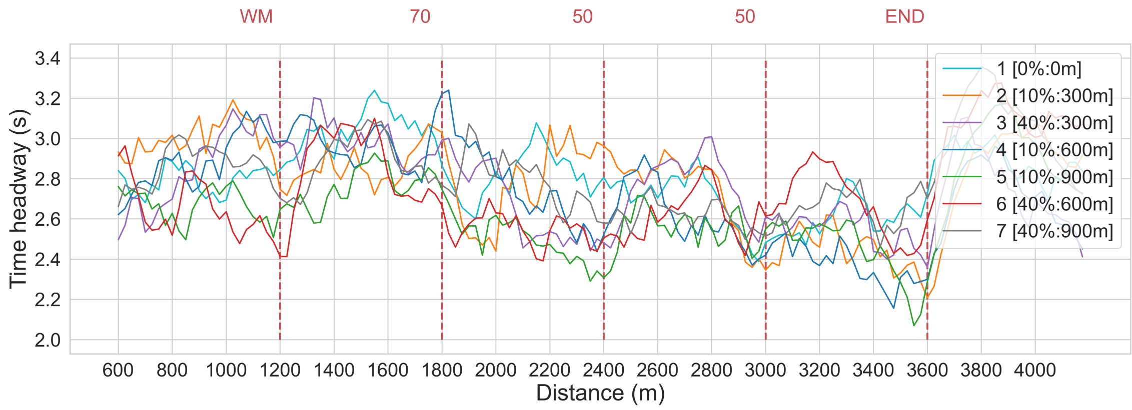


Figure 6.2: Visualization of average THW of all participants per scenario S[P:D] where S: scenario, P: penetration rate, D: distance upstream

The section average THW is presented in table Table 6.4. Considering the THW no large ranges (Ra) between scenarios are found for the sections. However, the same decreasing trend in average THW can be observed from the AP section until the 50_2 section. The lowest average THW occurs in the last road section 50_2.

Table 6.4: Scenario and section time headway mean (s) including section average (Av) and section range (Ra)

	Section				
Scenario	**WA**	**AP**	**70**	**50_1**	**50_2**
1 [0%:0m]	2.78	3.00	2.95	2.76	2.64
2 [10%:300m]	3.12	3.01	2.93	2.83	2.48
3 [40%:300m]	2.81	3.12	2.79	2.90	2.62
4 [10%:600m]	2.94	3.28	2.96	2.80	2.48
5 [10%:900m]	2.76	2.86	2.57	2.60	2.53
6 [40%:600m]	2.79	2.96	2.64	2.70	2.74
7 [40%:900m]	2.93	2.95	2.86	2.67	2.83
Av	2.88	3.03	2.81	2.75	2.62
Ra	0.36	0.42	0.39	0.23	0.35

6.2 Lateral behavior

The lateral behavior indicators are presented as scenario and section averages. Both the number of lane changes and the duration of lane changes are analyzed and presented below.

6.2.1 Number of lane changes

The average number of lane changes per scenario are visualized in the box plots in Figure 6.3. The black line in the box represents the median and the green line indicates the mean. Both the mean and median are fairly constant for all scenarios. Only the variation of scenario one stands out where higher values are observed.

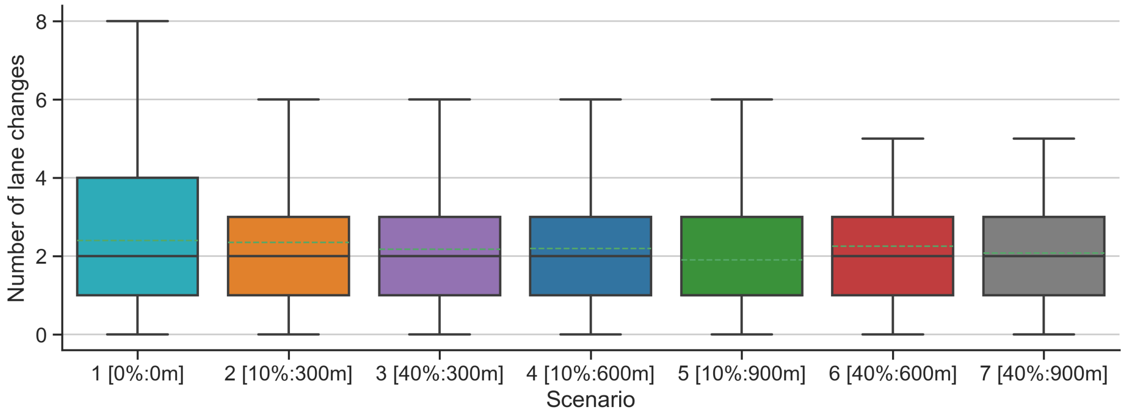


Figure 6.3: Number of lane changes per scenario

Next, the lane changes are analyzed in more detail for the road sections. The number of lane changes per scenario and section combination are set out in Table 6.5. A total of 1106 lane changes are observed which results in an average of 31.6 observations per scenario and section combination. The most lane changes per scenario are made in scenario 1 [0%:0m]. Moreover, in scenario 1 [0%:0m] and section WA the most lane changes are observed for all sections. The largest range within the sections for the scenarios are in section WA and 50_1 and 70. The frequency of lane changes, average 2.13 per run, is too low to investigate them on a more detailed level than section averages.

Table 6.5: Average lane changes per scenario and section combination, number of observations (Obs), scenario averages (Av), section averages (Av) and rang (Ra)

	Section						
Scenario	**WA**	**AP**	**70**	**50_1**	**50_2**	**Av**	**Obs**
1 [0%:0m]	0.57	0.36	0.49	0.53	0.46	2.40	173
2 [10%:300m]	0.49	0.38	0.42	0.49	0.53	2.29	169
3 [40%:300m]	0.40	0.35	0.44	0.42	0.49	2.10	157
4 [10%:600m]	0.35	0.33	0.44	0.50	0.50	2.13	158
5 [10%:900m]	0.44	0.38	0.31	0.32	0.42	1.86	137
6 [40%:600m]	0.38	0.38	0.43	0.44	0.53	2.15	162
7 [40%:900m]	0.28	0.36	0.49	0.49	0.43	2.04	150
Av	0.41	0.36	0.43	0.45	0.48	2.14	158
Ra	0.29	0.05	0.18	0.21	0.11	0.54	36

6.2.2 Duration of lane change

The average number of lane changes per scenario are visualized in the box plots in Figure 6.4. The black line in the box represents the median and the green line indicates the mean. The mean duration of a lane changes ranges per scenarios ranges between 2.66s (scenario 7) to 2.89s (scenario 1).

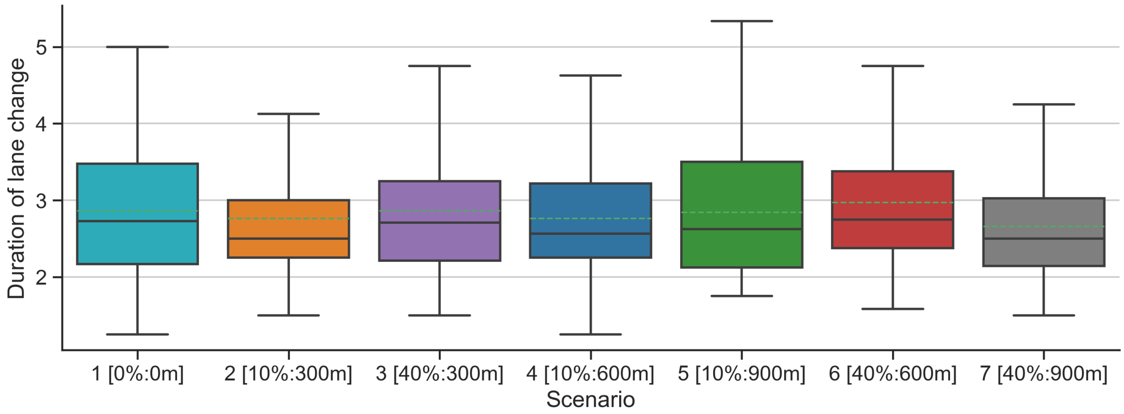


Figure 6.4: Duration of lane change per scenario

Considering the sections drivers make shorter lane changes in the first two sections, WA and AP, and take longer for their lane changes in the lower speed limit sections, see Table 6.6.

Table 6.6: Average lane change duration (s) per scenario and section including section averages (Av) and scenario averages (Av)

	Section					
Scenario	**WA**	**AP**	**70**	**50_1**	**50_2**	**Av**
1 [0%:0m]	2.68	3.06	2.92	2.95	2.81	2.89
2 [10%:300m]	2.65	2.71	2.78	3.10	2.92	2.83
3 [40%:300m]	2.68	2.70	3.14	3.00	2.90	2.88
4 [10%:600m]	2.86	2.79	2.63	2.83	2.88	2.80
5 [10%:900m]	3.26	2.35	2.90	2.82	2.72	2.81
6 [40%:600m]	2.69	2.58	2.85	2.96	3.13	2.84
7 [40%:900m]	2.28	2.80	2.52	2.99	2.69	2.66
Av	2.73	2.71	2.82	2.95	2.86	2.81

6.3 Driving style

In this section the indicators are analyzed for two different participants groups. Two groups are created from the sample based on self reported driving style. For both social and aggressive driving style groups of 7 participants are selected based on their driving index. The distribution of the driving index is presented in Figure 6.5. The average driving index of the 7 most aggressive drivers is 44.4 and 77.0 for social drivers. Selecting seven participants results in 14 observations per scenario and driving style combination. In the box plots below the indicator values are total run averages except for the total time speeding. From the plots the difference between the two groups can be observed per scenario and the effect of penetration rate and upstream information can be observed by comparing different scenarios.

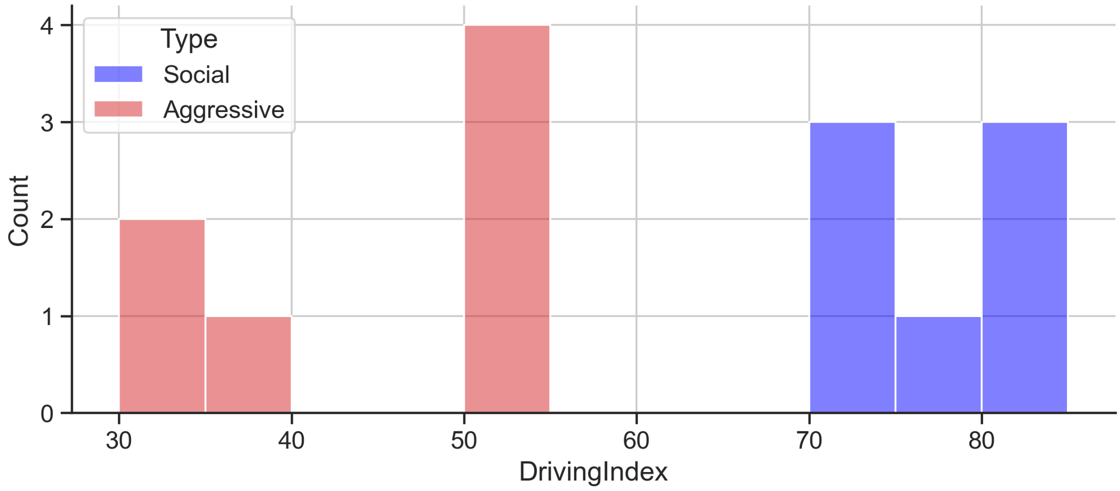


Figure 6.5: Distribution of driving index for social and aggressive driver groups

6.3.1 Mean speed

The visualization of the mean speed and variance per scenario per driving group is displayed in Figure 6.6. The green line represents the mean speed, the topside of the box is the 75$^{\text{th}}$ percentile and the bottom side of the box is the 25$^{\text{th}}$ percentile.

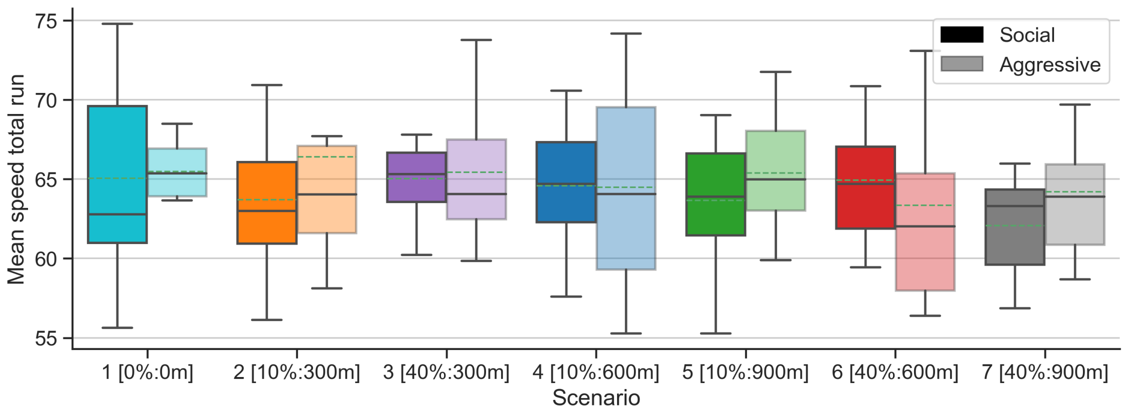


Figure 6.6: Mean speed (km/h) per scenario for both driving styles

The mean speed can be found in Table 6.7. The mean speed over the total run is relatively similar within scenarios 1, 3 and 4 for the two driving style groups. For scenarios 2, 5, 6 and 7 slightly larger differences are found. The variation in mean speed is quite large for different scenarios and this is probably caused by the small sample size of 14 observations per scenario and driving style combination. It is interesting to see that the difference in mean speed between the two groups is relatively low. Larger differences would be expected when only the most social and aggressive drivers are selected.

Table 6.7: Mean speed (km/h) per scenario and driving style group

	Scenario						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Social	65.06	63.70	65.04	64.58	63.65	64.94	62.08
Aggressive	65.49	66.40	65.44	64.48	65.39	63.35	64.21

6.3.2 Speed compliance

For the speed compliance varying results are found when comparing which driving style group has a higher total speeding time as can be seen in both Figure 6.7 and Table 6.8. It can be seen that self reported aggressive drivers do not consistently exceed the speed limit more than social drivers. The smallest differences between the two groups can be found in scenario 1 and 4 which have low (0 and 10%) penetration rates.

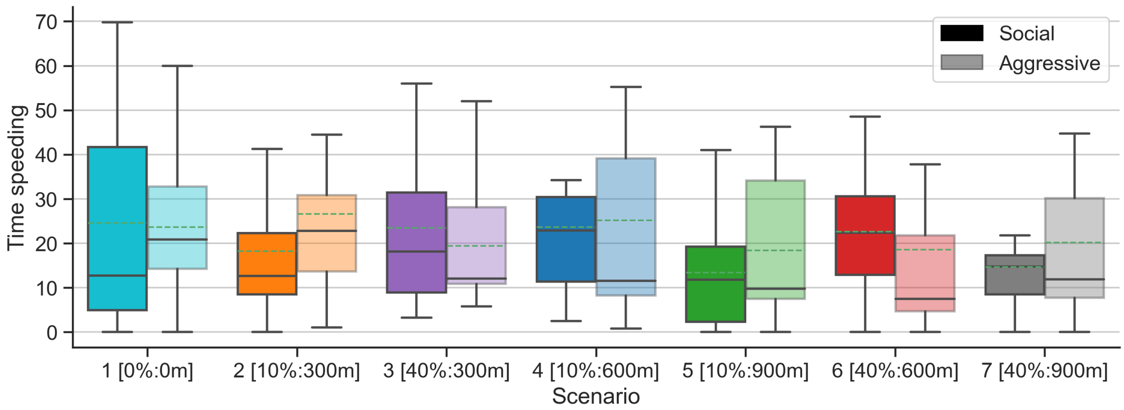


Figure 6.7: Total time 10% above the speed limit (s) per scenario for both driving styles

Table 6.8: Total time 10% above the speed limit (s) per scenario and driving style group

	Scenario						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Social	24.54	18.20	23.44	23.46	13.26	22.61	14.68
Aggressive	23.61	26.61	19.38	25.14	18.38	18.57	20.13

6.3.3 Time headway

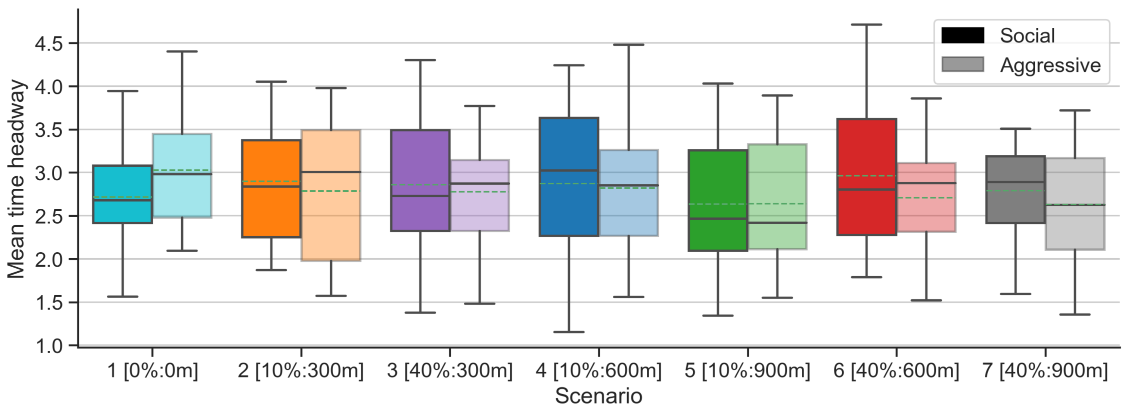


Figure 6.8: Mean time headway per scenario for both driving styles

The average THW per scenario is relatively stable over the different scenarios for both driving style groups. What stands out is that for most scenarios the aggressive drivers keep slightly shorter THWs. This is in line with the expectation that aggressive drivers keep shorter THWs.

Table 6.9: Mean time headway (s) per scenario and driving style group

	Scenario						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Social	2.72	2.90	2.86	2.87	2.63	2.96	2.79
Aggressive	3.03	2.78	2.78	2.82	2.64	2.71	2.63

6.3.4 Number of lane changes

Similar to the THW indicator, the aggressive driving style can be traced back into the results of the number of lane changes. Except for scenario 1 [0%:0m] and 7 [40%:900m] aggressive drivers make more lane changes than the social drivers, as presented in Figure 6.9 and Table 6.10.

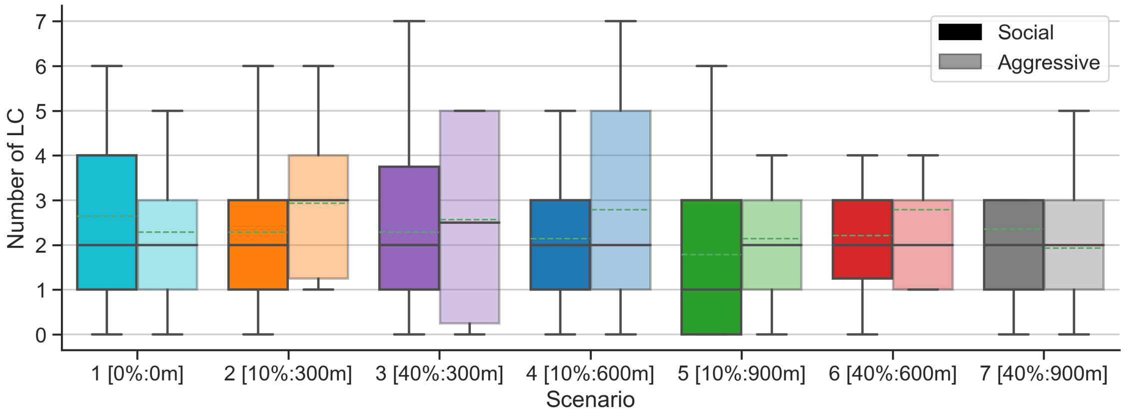


Figure 6.9: Number of lane changes per scenario for both driving styles

Table 6.10: Number of LC per scenario and driving style group

	Scenario						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Social	2.64	2.29	2.29	2.14	1.79	2.21	2.36
Aggressive	2.29	2.93	2.57	2.79	2.14	2.79	1.93

6.3.5 Duration of lane changes

The duration of lane changes varies between the two different groups and scenarios, as displayed in Table 6.11. The duration of lane changes are averages per drive for each scenario for both groups.

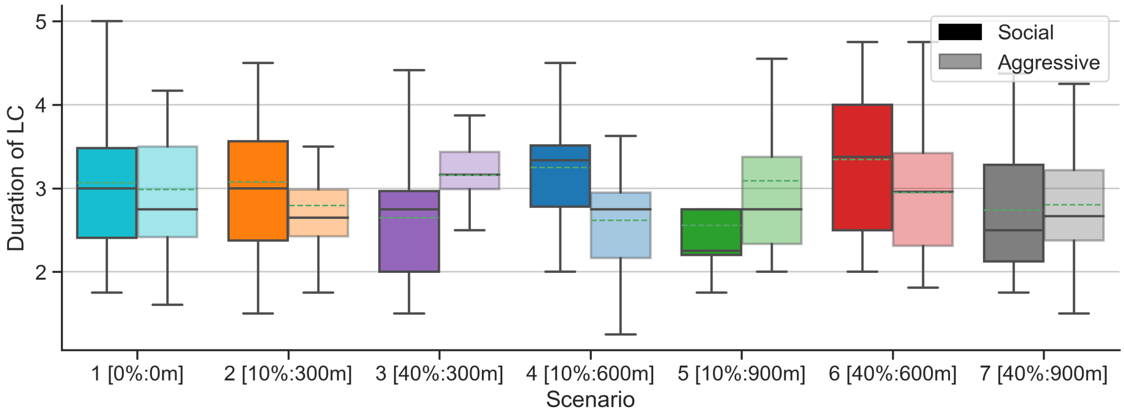


Figure 6.10: Duration of lane change per scenario for both driving styles

The mean values are presented in Table 6.11 below.

Table 6.11: Duration of LC per scenario and driving style group

	Scenario						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Social	3.07	3.08	2.65	3.25	2.56	3.35	2.74
Aggressive	2.99	2.80	3.16	2.62	3.09	2.95	2.80

In this chapter the data collected in this research is set out to get a better understanding for further analysis. Interesting differences are found the longitudinal driving behavior of the participants. Less distinct results are found for the lateral driving behavior. In the next chapter the results are compared in more detail for specific scenario combinations with statistical tests.

7. Hypothesis testing

In this chapter the hypothesis formulated in section 2.6 are tested. The effect of both penetration rate and upstream information are tested for the different levels of the other variable. This means that the effect of penetration rate is tested for three levels of upstream information, 300m, 600m and 900m. The effect of upstream information is tested for two levels of penetration rate, 0% and 40%. For each tested variable a summary is presented after the different levels are analyzed.

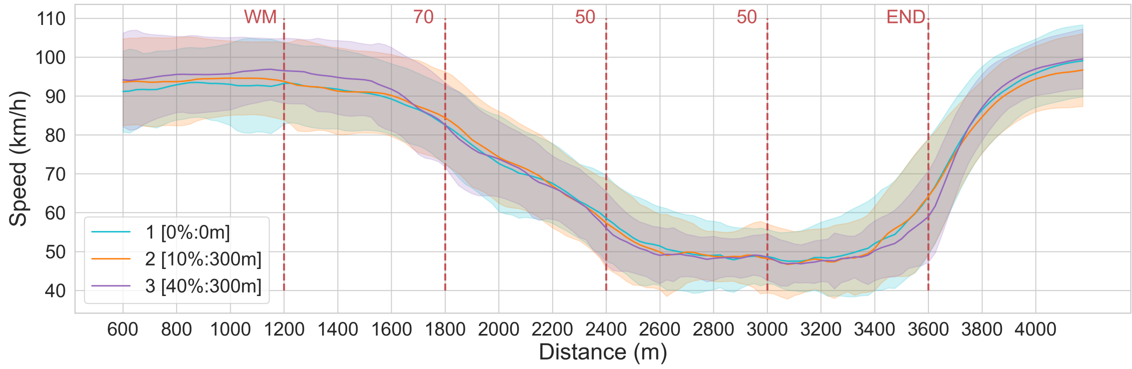
Because no difference was found between run 1 and run 2, both runs are treated as they come from the same sample. This increases the number of observations per scenario to a total of 72, that is two times the number of participants. The averaged indicators do not follow a normal distribution, which means non-parametric tests need to be used. In order to test differences in mean values between the different indicators per scenario and section a Friedman test is executed. The Friedman test allows for testing multiple samples at the same time. This means that all scenarios can be compared per section for each indicator. The significance level is set to a p-value of 0.05. Significant results are highlighted by a bolt font. When the Friedman has a significant result ($\alpha = 0.05$) a post-hoc test is used. For the post hoc test a non-parametric test needs to be used which is able to compare two sample means. In this case, the non-parametric test that is used is the Wilcoxon signed ranked test. The significant results are highlighted with a bolt font as well.

7.1 Penetration rate

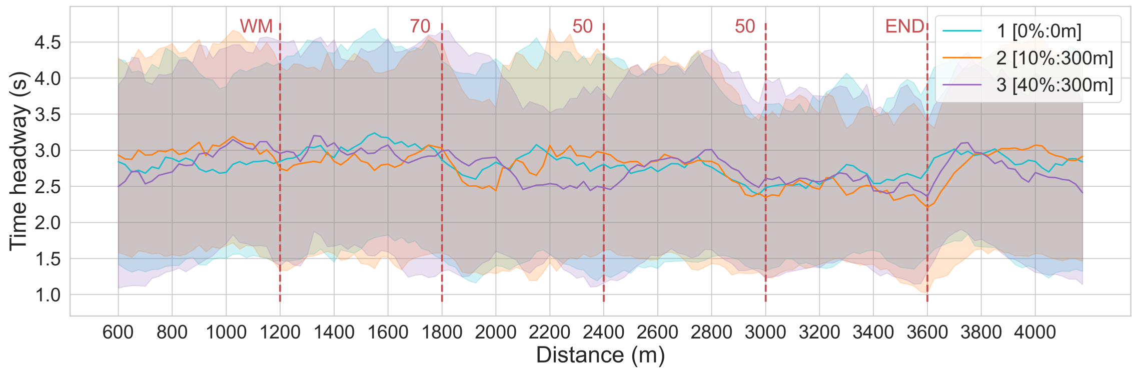
In this section the hypotheses for the effect of market penetration of CAVs are answered. The effect of penetration rate is analyzed for the three levels of upstream information separately. Next to the statistical testing the plots are added to support visual understanding of the test results. Each plot contains three scenarios with a constant upstream information distance and variable penetration rate of CAVs. For the penetration rate hypothesis the indicators mean speed, entry speed, speed compliance and THW are investigated.

7.1.1 Effect of penetration rate without upstream information

Figure 7.1 gives a more detailed presentation of the speed and THW behavior of the subject vehicles for the three levels of penetration rate without upstream information (scenarios 1 [0%:0m], 2 [10%:300m] and 3 [40%:300m]). The bandwidth in the plot indicates the standard deviation of the mean line.



(a) Speed



(b) Time headway

Figure 7.1: Average speed (a) and THW (b) of all participants for without upstream information including standard deviation

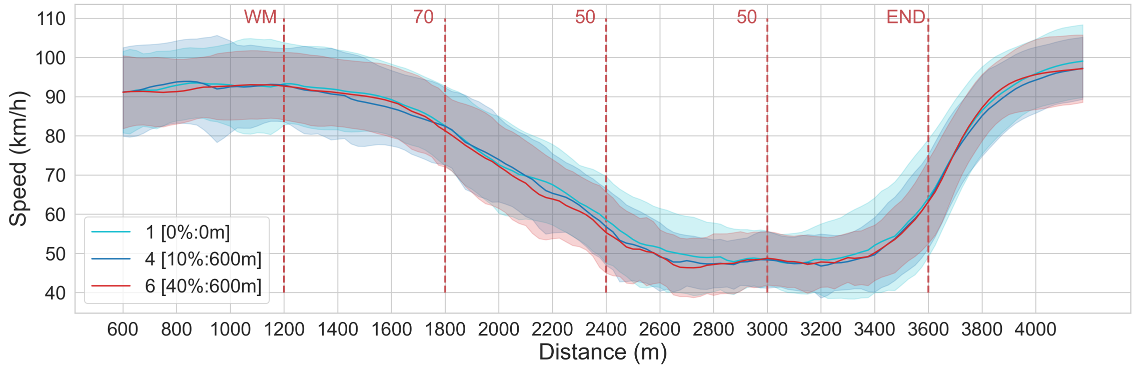
All indicators for the hypotheses for the effect of penetration rate are tested on significant differences per scenario and section combination. The test results of the Friedman test are presented in Table 7.1. With a p-value of 0.05 none of the indicators are significant for any of the scenario and section combination.

Table 7.1: Friedman [(Chi-Square), P-value] result of all indicators per section for different penetration rate without upstream information

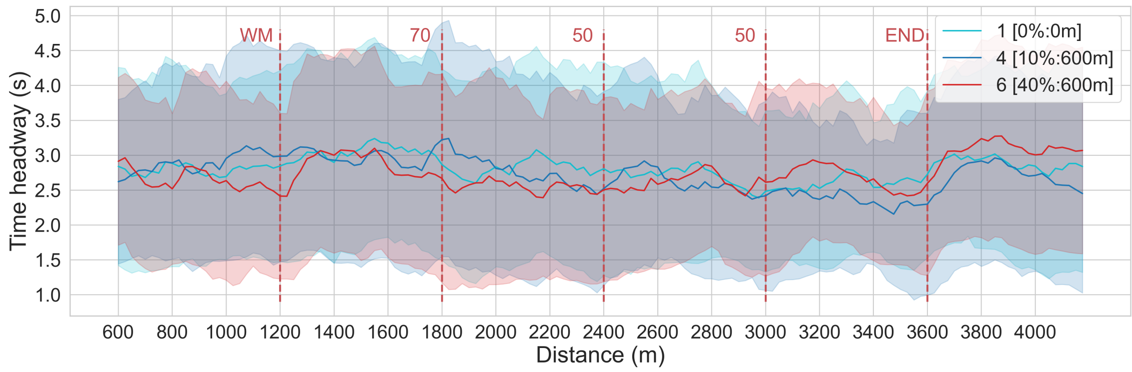
	Section			
	AP	**70**	**50_1**	**50_2**
Mean speed	(4.694), 0.096	(0.361), 0.835	(1.194), 0.550	(0.028), 0.986
Entry speed	(3.000), 0.223	(0.750), 0.687	(2.194), 0.334	(0.583), 0.747
Speeding	(1.879), 0.391	(0.276), 0.871	(4.507), 0.105	(1.135), 0.567
THW	(0.533), 0.766	(1.485), 0.476	(0.353), 0.838	(0.206), 0.902

7.1.2 Effect of penetration rate with 600m upstream information

In Figure 7.2 the two scenarios 4 [10%:600] and 6 [40%:600m] are presented and the base scenario 1 [0%:0m] is included.



(a) Speed



(b) Time headway

Figure 7.2: Average speed (a) and THW (b) of all participants with 600m upstream information including standard deviation

Again, all indicators for the hypothesis for the effect of penetration rate are tested on significant differences per scenario and section combination. The test results of the Friedman test are presented in Table 7.2. With an ($\alpha = 0.05$) only the entry speed in section 50_1 gives a significant result. In order to find out which of the three scenarios significantly differ from each other, a post hoc test is needed. As mentioned before, the Wilcoxon signed rank test is used. The results are provided in Table 7.3. For the pair-wise comparison the significance level is set at a p-value of 0.05 as well. This results in no significant results for any of the pairs.

Table 7.2: Friedman [(Chi-Square), P-value] result of all indicators per section for different penetration rate with 600m upstream information

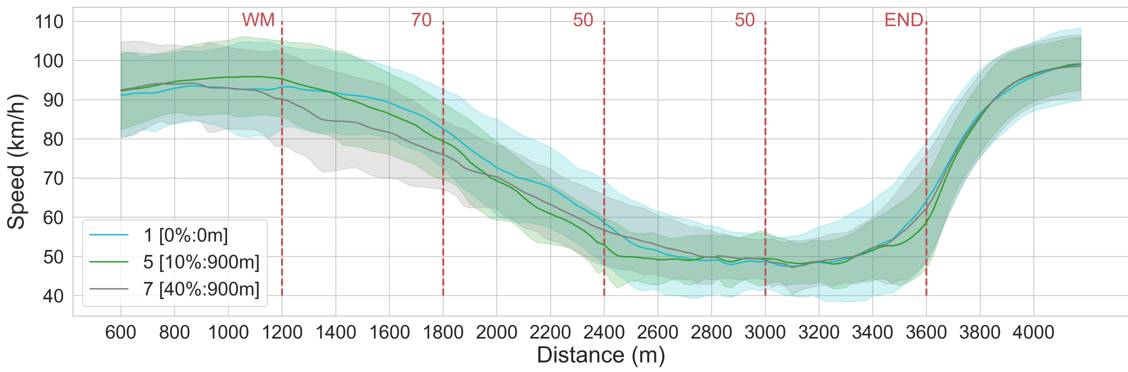
	Section			
	AP	**70**	**50_1**	**50_2**
Mean speed	(4.111), 0.128	(4.111), 0.128	(2.778), 0.249	(1.444), 0.486
Entry speed	(1.750), 0.417	(2.111), 0.348	(6.194), **0.045**	(0.250), 0.882
Speeding	(2.273), 0.321	(0.355), 0.837	(2.098), 0.350	(0.029), 0.985
THW	(0.525), 0.769	(5.727), 0.057	(0.636), 0.727	(3.908), 0.142

Table 7.3: Pair-wise penetration rate comparison of entry speed for a fixed distance of 600 and base scenario

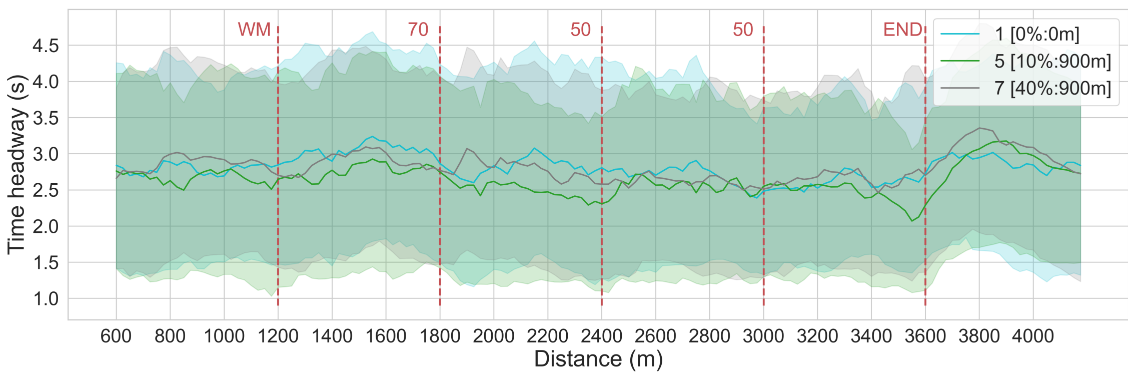
	Entry speed (kmph)			(Z-value), P-value		
Section	0%	10%	40%	0% - 10%	0% - 40%	10% - 40%
50_1	58.55	56.78	55.31	(-0.993), 0.321	(-1.639), 0.101	(-1.599), 0.110

7.1.3 Effect of penetration rate with 900m upstream information

Figure 7.3 presents the two scenarios, 5 [10%:900m] and 7 [40%:900m], with varying levels of penetration rates of CAVs for a fixed distance of 900 m including the base scenario 1 [0%:0m] without CAVs and no upstream information.



(a) Speed



(b) Time headway

Figure 7.3: Average speed (a) and THW (b) of all participants with 900m upstream information including standard deviation

The indicators corresponding to the penetration rate hypothesis are tested on potential differences between scenarios with the use of the Friedman test. The results are presented in Table 7.4 below. As can be seen, much more scenario and section combinations have significant results indicating that differences are present. However, still no significant results are found for a difference in THW. In order to find out which scenarios are significantly different per indicator and segment a Wilcoxon signed rank test is used.

Table 7.4: Friedman [(Chi-Square), P-value] result of all indicators per section for different penetration rate with 900m upstream information

	Section			
	AP	**70**	**50_1**	**50_2**
Mean speed	(19.000), **<0.001**	(13.028), **0.001**	(0.694), 0.707	(0.361), 0.835
Entry speed	(3.083), 0.214	(23.444), **<0.001**	(13.361), **0.001**	(0.528), 0.768
Speeding	(3.920), 0.141	(9.959), **0.007**	(9.143), **0.010**	(2.160), 0.340
THW	(0.413), 0.814	(5.182), 0.075	(2.985), 0.225	(0.388), 0.824

Penetration rate has a significant effect on the mean speed in combination with a distance of 900m for upstream information, see Table 7.5. The significant differences occur in sections approach and 70. In the approach section a penetration rate of 40% (82.61kmph) results in a significant lower mean speed compared to 0% (89.69kmph) and 10% (88.19kmph). In the 70 section both 10% (64.71kmph) and 40% (65.77kmph) lower the mean speed compared to 0% (69.63kmph) but do not differ statistically from each other.

Table 7.5: Pair-wise penetration rate comparison of mean speed for a fixed distance of 900 and base scenario

	Mean speed (kmph)			**(Z-value), P-value**		
Section	0%	10%	40%	0% - 10%	0% - 40%	10% - 40%
AP	89.69	88.19	82.61	(-0.982), 0.326	(-4.444), **<0.001**	(-3.328), **0.001**
70	69.93	64.76	65.77	(-3.608), **<0.001**	(-2.609), **0.009**	(-0.348), 0.728

A significant difference is observed for the indicator entry speed for sections 70 and 50_1 which is presented in Table 7.6. In the 70 section all three penetration rates, 0% (82.56), 10% (79.38) and 40% (75.94), statistically differ significantly from each other. In the 50_1 section only 10% (53.00) leads to a decrease in speed compared to 0% (58.55) and for 40% (56.17) no significant difference is found.

Table 7.6: Pair-wise penetration rate comparison of entry speed for a fixed distance of 900 and base scenario

	Entry speed (kmph)			**(Z-value), P-value**		
Section	0%	10%	40%	0% - 10%	0% - 40%	10% - 40%
70	82.56	79.38	75.94	(-2.593), **0.010**	(-3.956), **<0.001**	(-2.458), **0.014**
50_1	58.55	53.00	56.17	(-3.541), **<0.001**	(-1.240), 0.215	(-2.340), **0.019**

Next to mean speed and entry speed, a significant difference is found for the indicator speed compliance, presented in Table 7.7. In the approach section both 10% (4.9) and scenario 40% (5.0) differ from 0% (8.1) but do not differ from each other. In section 70 section 10% (8.2) results in less speeding compared to both scenario 0% (10.2) and 40% (13.3) but 0% and 40% do not differ statistically.

Table 7.7: Pair-wise penetration rate comparison of time speeding for a fixed distance of 900 and base scenario

	Speeding (s)			**(Z-value), P-value**		
Section	0%	10%	40%	0% - 10%	0% - 40%	10% - 40%
70	8.1	4.9	5.0	(-2.846), **0.004**	(-2.128), **0.033**	(-0.283), 0.777
50_1	10.2	8.2	13.3	(-2.224), **0.026**	(-0.067), 0.946	(-2.592), **0.010**

7.1.4 Effect of penetration rate H.1

To gain insight on the effect of penetration rate of CAVs on the driving behavior of HDV drivers the penetration rate is researched for three different levels of upstream information. The results are statistically tested with a confidence level of 95%. The results are compared to the hypotheses formulated in section 2.6. The reference numbers are connected to the hypothesis presented in Table 2.2.

H1.1 Mean speed

The mean speed was expected to decrease with increasing levels of penetration rate. Without upstream information no effect is found for both levels of penetration rate (10% & 40%) on the mean speed. The same result is found for both levels of penetration rate in combination with 600m upstream information. Only at a distance of 900m upstream information the effect of penetration rate on the mean speed becomes significant. Considering a penetration rate of 10% the mean speed is decreased in the 70 section by 7.5%. At a penetration rate of 40% the speed is reduced in both the approach and 70 section by 7.9% and 5.9%.

The hypothesis that penetration rate has an impact on the mean speed can only partly be accepted. Only when the introduction of CAV is combined with a large distance of upstream information the effect of penetration rate becomes apparent. An increase in penetration rate results in lower mean speeds in the beginning of the speed reduction.

H1.2 Section entry speed

The entry speed of the different sections was expected to decrease with increasing levels of penetration rate. Similar to the mean speed only significant changes are found for penetration rate in combination with a distance of 900m for upstream information. The entry speeds for sections where a new reduced speed limit is presented are decreased by the presence of CAV on the road in combination with 900m upstream information. When only 10% of traffic consists out of CAVs the entry speed of the 70 section is decreased by 3.9% and the entry speed of the first 50 section is decreased by 9.5%. When the penetration rate increases to 40% only the entry speed of the 70 section decreases by 8.0%.

Similar to the mean speed the hypothesis of the entry speed can only partly be accepted. The effect of penetration rate is only visible in combination with a large distance of upstream information. A penetration rate of 10% results in a lower entry speed in the 70 and first 50 section whereas a further increase in penetration rate to 40% only results in a lower entry speed at the 70 portal. However, the decrease in entry speed at the 70 portal is larger for a higher penetration rate.

H1.3 Speed compliance

The speed compliance was expected to increase with the introduction of CAVs on the motorway. Comparable to the previous indicators only a significant result is found in combination with a distance of 900m for upstream information. The speed compliance increased in the sections where a new reduced speed limit is active for both levels of penetration rate compared to the base scenario without CAVs. In the 70 section both penetration rates of 10% and 40% lead to almost the same decrease in average time speeding of 3s. In the first 50 section a decrease in speeding of 2 seconds is accomplished with a penetration rate of 10%. For a penetration rate of 40% an increase in speeding is observed but this result in not statistically significant.

The hypothesis for the effect of penetration rate of CAVs on the speed compliance is rejected. Although less speeding is observed for in the 70 section no difference is found between the two penetration rates in that section. Besides, in the following 50 section only a penetration rate of 10% results in less speeding where 40% has no effect. This means that no clear effect of penetration rate on the speed compliance is found.

H1.4 Time headway

The THW was expected to increase with increasing level of penetration rate. However, no significant change is found between any of the penetration rate levels. This means that participants keep the same THW for different levels of penetration rate at multiple distances of upstream information.

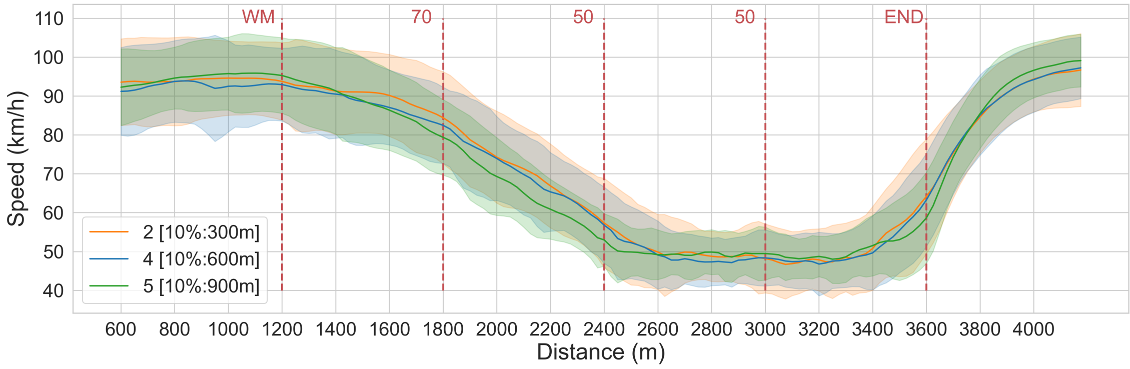
Therefore, the hypothesis that the THW increases with increasing levels of penetration rates of CAVs is rejected.

7.2 Upstream information

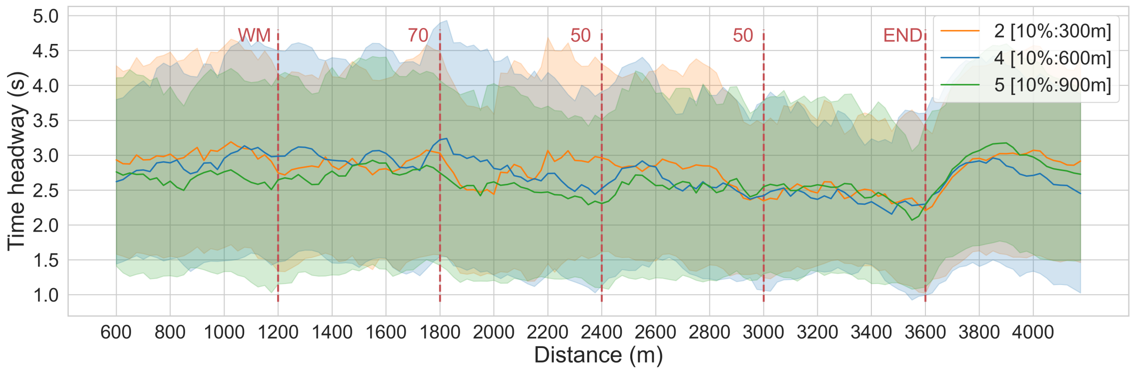
The indicators for the hypothesis of upstream information are tested in this section. The effect of upstream information is tested for two levels of market penetration. Scenario 1 [0%:0m] is excluded because no upstream information can be provided if no CAVs are present on the road. In each plot three scenarios are visualized corresponding to a different level of upstream information, 300, 600 and 900m. The first subsection describes the effect of upstream information at a penetration rate of 10% and the second subsection describes the effect for a penetration rate of 40%. The hypothesis of upstream information makes use of the same indicators as described above with the addition of the indicator number of lane changes.

7.2.1 Effect of upstream information at 10% penetration rate

First, the effect of upstream information at a penetration rate of 10% is analyzed. Figure 7.4 shows the plots of the mean speed and THW of the three scenario with 10% penetration rate and varying levels of upstream information (scenarios 2 [10%:300m], 4 [10%:600m] and 5 [10%:900m]) .



(a) Speed



(b) Time headway

Figure 7.4: Average speed (a) and THW (b) of all participants at a penetration rate of 10% including standard deviation

Again, the Friedman test is used to compare the three scenarios per road section. The mean speed shows a significant result in the 70 section. For entry speed significant differences are found for both the 70 and 50_1 sections. Similar to the entry speed, the speed compliance shows significant differences in the same sections. The THW indicator has no significant differences and the number of lane changes has a significant p-value in section 50_1. These findings are tested in more detail with a pairwise comparison.

Table 7.8: Friedman [(Chi-Square), P-value] result of all indicators per section for different distances of upstream information with 10% penetration rate

	AP	**70**	**50_1**	**50_2**
Mean speed	(2.111), 0.348	(16.361), **<0.001**	(0.194), 0.907	(1.333), 0.513
Entry speed	(5.861), 0.053	(9.083), **0.011**	(8.778), **0.012**	(3.083), 0.214
Speed compliance	(1.515), 0.469	(10.125), **0.006**	(8.213), **0.016**	(0.890), 0.641
THW	(0.295), 0.863	(3.086), 0.214	(1.652), 0.438	(1.486), 0.476
Number of LC	(0.230), 0.891	(2.413), 0.299	(6.497), **0.039**	(1.948), 0.377

The mean speed in section 70 shows a significant difference 900m (64.76) compared to 300m (70.08) and 600m (69.18). No significant difference is found between 300m and 600m.

Table 7.9: Pair-wise upstream distance comparison of mean speed for a penetration rate of 10%

	Mean speed (kmph)			(Z-value), P-value		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
70	70.08	69.18	64.76	(-0.572), 0.567	(-3.973), **<0.001**	(-3.687), **<0.001**

The entry speed is significantly different in two sections, 70 and 50_1. In the 70 section the same result is found for the mean speed. In the 70 section a significant difference for 900m upstream information (79.38) is found compared to 300m (84.42) and 600m (82.48). And again, no significant difference between 300m and 600m. In the first 50 section the same results are observed. Only 900m (53.00) has a significant effect on the entry speed compared to 300m (57.35) and 600m (56.78).

Table 7.10: Pair-wise upstream distance comparison of entry speed for a penetration rate of 10%

	Entry speed (kmph)			(Z-value), P-value		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
70	84.42	82.48	79.38	(-1.397), 0.162	(-3.670), **<0.001**	(-2.149), **0.032**
50_1	57.35	56.78	53.00	(-0.062), 0.951	(-2.666), **0.008**	(-2.694), **0.007**

The speed compliance shows almost the same result as the entry speed indicator. In the 70 section significant differences are found for both 900m (4.9) and 600m (7.8) compared to 300m (8.8). However, for the 50_1 section only a significant difference is found between 900m (8.2) and 2 (8.9) and no significant difference is found for 600m (8.4) with either 300m or 900m. It can be seen that the speed compliance difference in the 70 section is larger than in the first 50 section.

Table 7.11: Pair-wise upstream distance comparison of time speeding for a penetration rate of 10%

	Speeding (s)			(Z-value), P-value		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
70	8.8	7.8	4.9	(-0.489), 0.625	(-3.401), **0.001**	(-3.0782), **0.002**
50_1	8.9	8.4	8.2	(-0.262), 0.937	(-2.311), **0.021**	(-1.550), 0.121

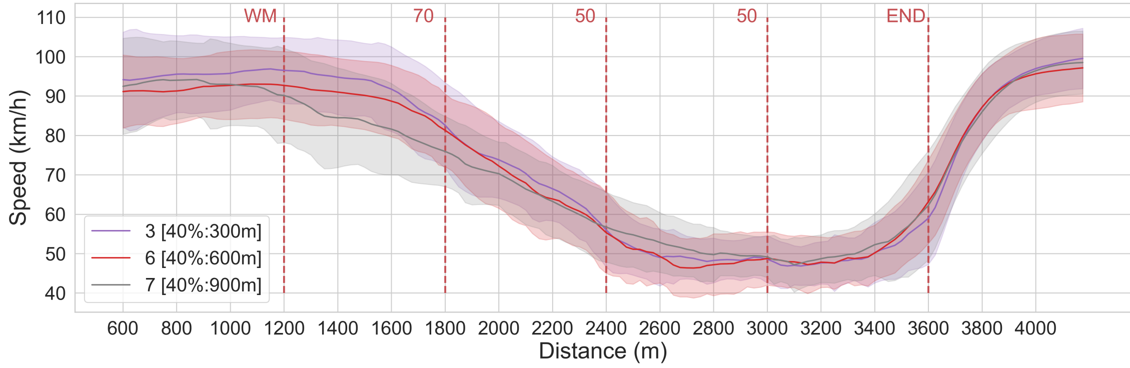
For the number of lane changes the Friedman test resulted in a significant difference for section 50_1, when comparing multiple samples at the same time. However, after a post hoc analysis no significant difference is found for the pair-wise comparison, see Table 7.12

Table 7.12: Pair-wise upstream distance comparison of number of lane changes for a penetration rate of 10%

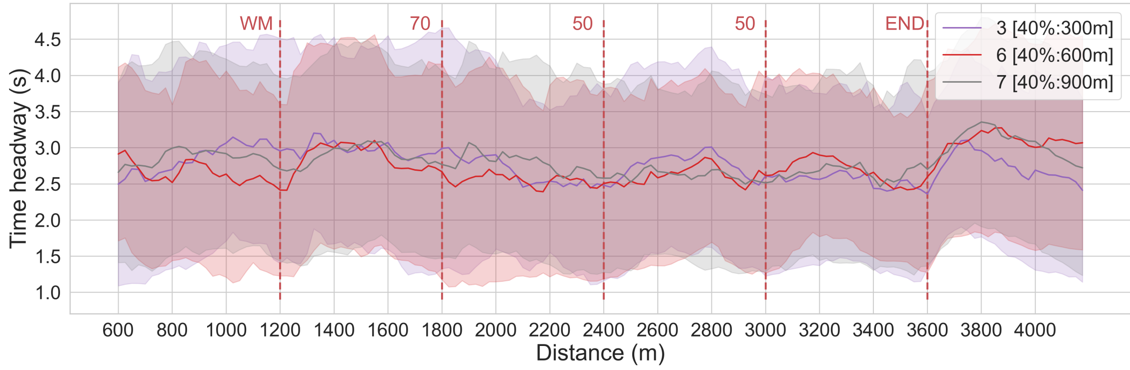
	Number of LC			(Z-value), P-value		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
50_1	0.49	0.50	0.32	(-0.169), 0.866	(-1.623), 0.105	(-1.623), 0.105

7.2.2 Effect of upstream information at 40% penetration rate

The indicators for the effect of upstream information are analyzed at a distance of upstream information of 900m. The three scenarios (3 [40%:300m], 6 [40%:600m] and 7 [40%:900m]) are visualized for the indicators speed and THW in the Figure 7.3 below.



(a) Speed



(b) Time headway

Figure 7.5: Average speed (a) and THW (b) of all participants at a penetration rate of 40% including standard deviation

The mean speed is significantly different for three consecutive sections, namely, approach, 70 and 50_1. The entry speed is only significant for the first two sections, approach and 70. The speed compliance has two sections with significant differences, which are the 70 and 50_1 sections. For THW and number of lane changes no significant results are found with the Friedman test. For the indicators with significant results the outcomes of the Wilcoxon signed rank test are presented in the tables below.

Table 7.13: Friedman [(Chi-Square), P-value] result of all indicators per section for different distances of upstream information with 40% penetration rate

	AP	**70**	**50_1**	**50_2**
Mean speed	(27.750), **<0.001**	(7.583), **0.023**	(13.528), **0.001**	(4.528), 0.104
Entry speed	(12.583), **0.002**	(12.028), **0.002**	(1.444), 0.486	(4.861), 0.088
Speed compliance	(4.455), 0.108	(9.711), **0.008**	(8.710), **0.013**	(1.823), 0.402
THW	(2.207), 0.332	(1.581), 0.454	(3.246), 0.197	(2.896), 0.235
Number of LC	(0.151), 0.927	(1.205), 0.547	(1.152), 0.562	(1.117), 0.572

The first section with a significant difference in mean speed is the approach section. In this section all three levels of distances of upstream information, 300m (92.00), 600m (88.95) and 900m (82.61) differ significantly. In the following section, 70, only 900m (65.77) results in a significant change in mean speed compared to 300m (69.18.). No difference is found for 600m (67.31) with either 300m or 900m. In section 50_1 the mean speed increases slightly in case of 900m of upstream information (51.48) compared to both 300m (49.42) 600m (48.37).

Table 7.14: Pair-wise upstream distance comparison of mean speed for a penetration rate of 40%

	Mean speed (kmph)			**(Z-value), P-value**		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
AP	92.00	88.95	82.61	(-2.576), **0.010**	(-5.511), **<0.001**	(-3.631), **<0.001**
70	69.18	67.31	65.77	(-1.055), 0.291	(-2.626), **0.009**	(-1.498), 0.134
50_1	49.42	48.37	51.48	(-1.257), 0.209	(-2.435), **0.015**	(-3.199), **0.001**

The entry speed shows significant differences in the approach and 70 sections which need a more detailed investigation. Both 600m (92.71) and 900m (90.15) lower the speed significantly compared to scenario 3 (96.52). However, the difference between 600m and 900m is not statically significant. In the 70 section only 900m (75.94) results in a statistically significant decrease in entry speed compared to 300m (82.58).

Table 7.15: Pair-wise upstream distance comparison of entry speed for a penetration rate of 40%

	Entry speed (kmph)			**(Z-value), P-value**		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
AP	96.52	92.71	90.15	(-2.682), **0.007**	(-4.080), **<0.001**	(-1.409), 0.159
70	82.58	81.31	75.94	(-0.567), 0.571	(-3.782), **<0.001**	(-3.030, **0.002**

The speed compliance is affected by upstream information in sections 70 and 50_1. In section 70 again only 900m (5.0) results in a significant difference from 3 (7.1). Similar to the previous section 900m (13.3) differs significantly from 300m (8.6) and 600m (8.5) for the 50_1 section. However, corresponding to the higher mean speed in this section the time spend speeding increases with a large distance of upstream information.

Table 7.16: Pair-wise upstream distance comparison of time speeding for a penetration rate of 40%

	Speeding (s)			**(Z-value), P-value**		
Section	300m	600m	900m	300m - 600m	300m - 900m	600m - 900m
70	7.1	7.0	5.0	(-0.274), 0.784	(-2.065), **0.039**	(-2.257),**0.024**
50_1	8.6	8.5	13.3	(-0.705), 0.481	(-2.273), **0.023**	(-2.133), **0.033**

7.2.3 Effect of upstream information

Three levels of upstream information are established. The effect of upstream information is researched for two levels of penetration rate. The results are statistically tested with a confidence level of 95%. The results are compared to the hypotheses formulated in section 2.6. The reference numbers are connected to the hypotheses presented in Table 2.2.

H2.1 Mean speed

The mean speed was expected to decrease with a larger distance of upstream information to CAVs. At a penetration rate of 10% the mean speed is only affected by 900m upstream information in the 70 section and is decreased by 7.6%. In other sections no change in mean speed is observed for either 600m or 900m compared to 300m of upstream information. When the penetration rate is increased to 40%, the effect of upstream information is higher. Both 600m and 900m of upstream information lead to a decrease in mean speed in the approach section by relatively 3.3% and 10.2%. Furthermore, 900m of upstream information results in a lower mean speed the 70 sections 70 by 4.9%. In the first 50 section the mean speed slightly increases with 900m of upstream information by 4.1%.

The hypothesis that the distance of upstream information decreases the mean speed is accepted. At a penetration rate of 10% a distance of 900m of upstream information lowers the mean speed in the 70 section. In combination with 40% penetration rate both 600m and 900m of upstream information result in a lower mean speed where the effect of 900m is larger compared to 600m.

H2.2 Entry speed

The section entry speed was expected to decrease with increasing levels of upstream information. At a penetration rate of 10% no differences in entry speed are found for a distance of 600m. However, if the speed limit is shared at a distance of 900m upstream, the entry speeds of sections 70 and 50_1 are lowered by 6.0% and 7.6%. At a penetration rate of 40% the entry speed is lowered by both distances of upstream information at the approach section by 3.9% for 600m and 6.6% with 900m. At the beginning of the following 70 section only 900m has a statically significant effect on the entry speed. It lowers the entry speed by 8.0%. No effect is found for the entry speed of the following 50 kmph sections.

The hypothesis that the effect upstream information can help lower the entry speed of sections is accepted. Upstream information of 900m contributes to lowering the entry speeds in sections 70 and 50_1. If the penetration rate increases to 40% a shorter distance of 600m helps to decrease the entry speed as well, but providing upstream information at 900m results in more and larger effects.

H2.3 Speed compliance

The speed compliance was expected to increase with increasing levels of upstream information. At a penetration rate of 10% the speed compliance is increased for section 70 for both 600m (1s) and 900m (3.9s) of upstream information compared to 300m. In the following 50 section only 900m of upstream information leads to an increase in speed compliance of 0.7s. At a penetration rate of 40% significant differences are found in speed compliance for a distance of 900m of upstream information in the 70 and 50_1 sections. In the 70 section the speed compliance is increased with 2.1s but for the 50_1 second the speed compliance decreases with 4.7s.

The hypothesis that upstream information results in a higher speed compliance can on partly be accepted. Taking into account a penetration rate of 10% CAVs the speed compliance is increased by upstream information where an increase of distance results in a higher compliance. The same result is found for the 70 section at a penetration rate of 40%. However, a decrease in speed compliance is observed for the first 50 section in combination with 900m of upstream information.

H2.4 Time headway

The THW was expected to increase with increasing levels of upstream information. However, no effect on THW is found when providing upstream information to CAVs.

Therefore, the hypothesis on the effect of upstream information on a decrease in THW is rejected.

H2.5 Number of lane changes

The number of lane changes was expected to increase with increasing levels of upstream information. No significant changes are found in the driving behavior of HDV drivers in terms of lane changes when providing upstream information.

As a result, the hypothesis of an increase in number of lane changes due to providing upstream information is rejected.

7.3 Driving style

The participant sample is divided over two driving style groups based on their self-reported driving style. Aggressive participants are selected on a low driving index and social drivers are selected on a high driving index. The run averages of the different indicators are tested per scenario between the two groups.

In order to investigate potential differences between social and aggressive drivers, the results presented in section 6.3 are tested for statistical significance. The mean values for each scenario are compared between the two driving style groups. A paired test, the Wilcoxon sign rank test, is used to compare two groups.

The test results are presented in Table 7.17 below. In the table it can be seen that for none of the indicators a significance level below 0.05 is reached. This means that no significant differences occur for any of the indicators in any of the scenarios between the two driving style groups.

Subsequently, all hypothesis for the effect of driving style on all driving indicators are rejected.

Table 7.17: Wilcoxon signed rank [(Z-value), P-value] test for two driving style groups per scenario and indicator

	(Z-value), P-value						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Mean speed	(-0.220), 0.826	(-0.596), 0.551	(-282), 0.778	(-0.157), 0.875	(-1.287), 0.198	(-0.847), 0.397	(-1.475), 0.140
Speed compliance	(-0.094), 0.925	(-1.287), 0.198	(-0.659), 0.510	(-0.157), 0.875	(-0.784), 0.433	(-0.847), 0.397	(-0.659), 0.510
Time headway	(-1.726), 0.084	(-0.659), 0.510	(-0.282), 0.778	(-0.031), 0.975	(-0.282), 0.778	(-0.596), 0.551	(-0.722), 0.470
Num. of LC	(-0.630), 0.529	(-1.281), 0.200	(-0.317), 0.751	(-910), 0.363	(-298), 0.766	(-0.320), 0.749	(-0.321), 0.748
Du. of LC	(-0.949), 0.342	(-1.648), 0.099	(-1.120), 0.213	(-1.245), 0.213	(-0.421), 0.674	(-1.153), 0.249	(-0.980), 0.327

7.3.1 Effect of driving style

It was expected that drivers with a more aggressive self-reported driving style would show different driving behavior. However, no significant differences are found for any of the indicators in any of the scenarios. Therefore, there is no need to present and test the separate indicators from the hypothesis in Table 2.2.

8. Discussion and conclusion

In the literature research (chapter 2) the potential benefits of connectivity between automated vehicles and the infrastructure are discussed. Multiple studies suggest that connectivity could lead to an improvement in both traffic safety and efficiency (Khondaker & Kattan, 2015a; Qi et al., 2020; X. Guo et al., 2020). Most of these studies do not incorporate the potential behavioral adaptation of human drivers in mixed traffic. However, a few studies have researched the behavioral adaptation of human drivers in mixed traffic. These studies found a decrease in THW of human drivers next to AV platoons (Gouy et al., 2014), a change in timing of a lane changes driving next to platoons (S. Lee & Oh, 2017), and more stable longitudinal speed profiles if human drivers follow an automated vehicle (Mahdinia et al., 2021). Therefore, this research contributes to fill this knowledge gap on behavioral adaptation for applications and traffic situations in mixed traffic.

One of the potential applications of connectivity is the provision of upstream information of upcoming speed limits to CAVs on a road equipped with a VSL system. In this research it is investigated if and how human drivers change their driving behavior when driving in mixed traffic where CAVs receive upstream information. This chapter is structured as follows. First, the results of the four sub questions are discussed. Second, a conclusion is drawn on the main research question. Last, the research is reflected and the limitations are presented.

8.1 Discussion

The goal of this study is to investigate potential behavioral adaptation of human drivers in a context with CAVs with upstream information on upcoming speed limits on motorways equipped with VSL signs. In order to find potential behavioral adaptations in varying context settings, four sub questions were formulated.

8.1.1 Discussion on penetration rate

The effect of CAVs on the driving behavior of human drivers is researched. Two penetration levels of 10% and 40% are compared to a base case without CAVs. The different levels of penetration rates are compared for fixed levels of upstream information which are 300m, 600m and 900m.

In the first case the introduction of CAVs is analyzed for no upstream information. No upstream information means that CAVs are able to detect the change in speed limit at only 300m before the VSL sign which is similar to the distance at which HDVs start to adapt their speed. This means that potential behavior adaptations are solely due to the difference in driving behavior of two vehicle types. The HDVs and CAVs differ in terms of preferred THW and speed compliance, where CAVs keep a longer THW and have less variability in speed. For all three penetration rates, no significant differences are found for any of the driving behavior indicators in any of the road sections. This means that introducing CAVs without upstream information (300m) does not lead to a change in driving behavior of HDV drivers. Therefore, the potential benefits of CAV in terms of traffic safety and efficiency can be questionable.

Compared to other behavioral adaptation studies (Gouy et al., 2014; S. Lee & Oh, 2017; Rahmati et al., 2019) presented in Table 2.1 the result that no behavioral adaptation is observed is surprising. One potential explanation could be that although differences are present between the two vehicle types, the differences are less distinct compared to the above-mentioned studies. Another explanation could be that CAVs were not recognisable in this study, which means that participants did not know which and how many of the surrounding vehicles were a CAV or HDV. This means that behavioral adaptation of HDV drivers is highly dependent on the parameters of the driving behavior of AVs in mixed. It can be concluded that incorporating behavioral adaptation of HDV drivers in mixed into microscopic models is not a straightforward exercise.

In case the penetration rate of CAVs is combined with upstream information at 600m still no differences in driving behavior of HDV drivers is observed for different levels of penetration rates. Only when the introduction of CAVs is combined with upstream information at a distance of 900m significant differences are found in driving behavior for the different levels of penetration rates. This can be a logical result because when providing more upstream information, the change in driving behavior of CAVs becomes more apparent. Nevertheless, it should be noted that for 600m upstream information this effect is not yet present. In combination with a large distance of upstream information (900m), HDV drivers tend to change their longitudinal driving behavior in terms of speed with increasing levels of penetration rate. The biggest difference with varying levels of penetration rate is the location at which HDV drivers start to adapt their speed. For a penetration rate of 10% drivers start to decelerate more upstream compared to 0%. When the penetration rate is increased to 40%, HDV drivers start to decelerate even more upstream compared to 0% and 40%. Once the a new reduced speed is shown for a second time no further effect are observed and drivers behave similar compared to a non mixed traffic situation. Furthermore, no differences are found for THW, number of lane changes and duration of lane changes. For this reason, it can be assumed that traffic slowing down more upstream does not result in human drivers showing more aggressive behavior.

It can be concluded that different levels of penetration rate of CAVs on itself does not induce behavioral adaptation, based on the scenarios whiteout upstream information, whereas it does in combination with a large distance of upstream information. This means that just adding AVs to the total traffic does not necessarily result into safer and more efficient traffic. Only when a specific application for CAVs, in this research connectivity with the infrastructure, is introduced simultaneously with the introduction CAVs a change in driver behavior can be expected. Other examples of applications of CAVs which induce behavioral adaptation is platooning (Gouy et al., 2014; X. Guo et al., 2020) and dedicated lanes for AVs (Schoenmakers et al., 2021).

8.1.2 Discussion on upstream information

The effect of upstream information to CAVs on the driving behavior of HDV drivers is researched. The effect is analyzed for three different distances, 300m, 600m and 900m. 300m was chosen as the base scenario because this is the first distance at which HDV drivers start to adapt their speed regarding the upcoming speed limit. The three levels of upstream information are analyzed for two fixed penetration rates, 10% and 40%. In case 10% of the vehicles of the total traffic was a CAV, significant differences are observed for a distance of 900m compared to 300m and 600m. This means that providing information at low penetration rates of CAVs only makes sense if the information is provided at a large distance upstream. In case the penetration rate increases to 40% more significant results are found. The effect of 900m upstream information is observed in more sections and for a distance of 600m upstream information driving behavior of HDV drivers changes as well but not to the same extent compared to 900m. The behavioral adaption induced by upstream information is only observed for longitudinal driving behavior. The speed compliance increases and the mean speed decreases in sections where a new reduced speed limit is presented. Besides, the entry speed into those road sections is lower as well. This means that providing upstream information to part of the traffic can contribute to slow down the rest of the traffic flow without inducing a change in driving behavior in terms of lane changes and THW.

It may be concluded that providing upstream information on the speed limit has the most effect if it is provided at a large distance upstream of the actual VSL. Furthermore, the benefits of upstream information are expanded when more CAVs are present on the road.

Thus, from this research it may be stated that combining a high penetration rate of CAVs with a large distance of upstream information can help to improve the traffic safety by slowing down traffic.

The results of this research are in line with other studies on speed compliance under VSL. The speed compliance is found to be lower at the first few VSL signs, which is similar to the results of Lee & Abdel-Aty (2008). Besides, the speed compliance is increased when CAVs receive upstream information at a large distance upstream and thus drive slower when approaching a VSL. This is similar to the results of a study done by Varotto et al., (2021b).

8.1.3 Discussion on driving style

The effect of different driving styles is investigated to answer the third sub research question. Aggressive drivers are compared to social drivers. Although differences were expected between the two groups, no difference in driving behavior is found in this research. This means that both groups behave similarly in terms of driving behavior and behavioral adaptation in this research set up. Despite no differences between the two driving style groups are found in this research, it can not be excluded that driving style has an impact on behavioral adaptation of HDV drivers in mixed traffic. It is possible that differences are found if a different method is used to select drivers for the two driving style groups.

8.1.4 Practical insights for road authorities

The last sub research question relates to the practical insights for road authorities gained from this research. From the results it can be concluded that providing upstream information to only part of the traffic can contribute to influencing the speed behavior of the total traffic flow without leading to negative behavioral adaptations in terms of more aggressive or unsafe driving behavior. In case a road authority would implement connectivity between the infrastructure and vehicles to communicate information on upcoming speed limits the following aspects should be taken into account.

A large distance of upstream information should be considered in order to influence the behavior of surrounding traffic. In this research the largest distance researched was 900m which is three times greater than the first distance at which human drivers normally would adapt their to a new speed limit on motorways. 900m is found to be a good distance since at this distance the speed behavior of HDV drivers was significantly reduced. 900m of upstream information already resulted in a change in driving behavior of HDV drivers at a penetration rate of 10% for CAVs. In case the penetration rate would further increase to 40% the effect on the driving behavior becomes even larger. This suggests that an increase in penetration rate would result in larger effects of behavioral adaptation.

For road authorities it is important to investigate how to implement a system where part of the traffic is used to slow down surrounding. The incentive for CAVs drivers is not obvious because they are the ones that are impacted most by reduced speed limits. Potential incentives could be road tax reductions or a discount on car insurance.

Communicating the speed limit to part of the traffic could be expanded to other use cases on the road. Potential examples are roadblocks or road construction sites with reduced speed limits, and coordination of speed limits to prevent or suppress shock waves on motorways (Schelling, Hegyi, & Hoogendoorn, 2011; Han, Chen, & Ahn, 2017). With an increased speed compliance to the posted speed limit, speed limit strategies can be more efficient and more detailed strategies can be applied.

8.2 Conclusion

The insights from the sub research question are used to formulate the conclusion on the main research question. The main question of this research is: **How do human drivers change their car-following, lane-changing and speed adaptation behavior in mixed traffic in combination with VSL on motorways?**

In this research it is found that HDV drivers do not change their lane-changing and car-following behavior in mixed traffic in combination with VSL on motorways. However, a change in speed adaptation is observed in case a large distance is chosen at which the speed limit is shared with CAV. Human drivers tend to reduce their speed earlier in case the surrounding traffic drives slower as well. This results in an overall lower mean speed in a VSL road segment, a higher speed compliance and lower entry speeds at the VSL sign locations where a new speed limit becomes active. With increased penetration rates of CAVs and a larger distance of upstream information these effects are observed more upstream relevant to the VSL sign location.

This supports the findings of previous studies on the benefits of CAVs in a context with VSL.

8.3 Contribution

This research contributes to the scientific and practical knowledge regarding mixed traffic and VSL. The main contributions are presented below.

8.3.1 Scientific contributions

Understanding of change in driving behavior of HDV drivers when interacting with CAVs in a VSL context.

There has been a lack of understanding of the potential changes in driving behavior of HDV drivers when interacting with CAVs which are provided with upstream information on upcoming VSL. Multiple studies have investigated the effect by making use of microscopic models. However, these models assume that HDV drivers show the same behavior in mixed traffic compared to HDV traffic. This research provides an empirical insight in the adaptation of driving behavior of HDV drivers. The insight can be used to update the driving behavior models used for microscopic modelling to increase the validity of the results.

Data set for future research on mixed traffic and VSL.

During the driving simulator experiment a lot of data is collected on the driving behavior of HDV drivers in mixed traffic in a VSL context. From the data set many other indicators can be computed to analyze the driving behavior.

8.3.2 Practical contributions

Recommendations for road authorities.

This research presents practical recommendations to authorities who are involved with the design and innovation of road infrastructure. Different penetration rates of CAVs are used to represent multiple future scenarios. The insights can be used to set goals regarding the preferred penetration rates in the future and to choose a distance for providing upstream information.

The research gives insight in the potential beneficial effect of providing upstream information on speed limits to part of the traffic. With this insight road authorities can decide on future research, alternative ways or other use-cases to provide upstream information to (part) of the traffic.

Insights for future driving simulator experiment.

For this research changes are made to driving behavior models used by the driving simulator. These adaptations can be adjusted or used for future driving simulator experiments. Moreover, Dutch VSL signs are successfully integrated in the driving environment which can be used in future driving simulator experiments involving VSL.

8.4 Reflection and limitations

The reflection of this research is divided over two subsections. In the first subsection the research is reflected in terms of the overall focus of this research and assumptions made on behavior of different type of vehicles in mixed traffic and the interaction with the infrastructure. The second subsection reflects on the method used in terms of the driving simulator and the data processing.

8.4.1 Reflection on research

In order to execute the driving simulator various decisions and assumption had to be made. These limitations are discussed below.

In this research the effect on the traditional human drivers in unequipped cars is analyzed. It was assumed that the penetration rate of CAV were fixed within the scenarios. However, in real-life, drivers of CAVs have the ability to either activate or deactivate the ACC functionality in their vehicles. In case CAVs will slow down more upstream due to the connectivity to the infrastructure, drivers may deactivate the ACC functionality. As a result, the penetration rate of active CAVs will reduce and the potential benefits to the traffic safety and flow are decreased. Moreover, this would lead to a variability in driving behavior for specific vehicles, whereas in this research this was fixed.

Furthermore, to isolate the effect of the driving behavior of CAVs on the driving behavior of HDV drivers, certain traffic elements were excluded. Examples are other type of vehicles as vans and trucks and other type of information systems as in-vehicle devices. In the real-world the composition of traffic is more heterogeneous which could affect the ability of CAV to slow down surrounding traffic. Besides, drivers are nowadays already provided with extra information on the upcoming traffic situation with the help of smartphones and apps as Google Maps and Flitsmeister. The combination of in-vehicle technology and CAVs cooperating with the infrastructure could lead to greater benefits.

8.4.2 Reflection on methodology

For this empirical experiment it was chosen to use a driving simulator. The implications of this choice to use a driving simulator are discussed below. Besides, the experimental design choices and data processing are reflected on.

Use of driving simulator

When using a driving simulator the long term effect cannot be tested with a driving simulator setup where participants only drive the scenarios at one moment. If this research were to be implemented in real life the tests should be done in various environments with different setups at different moments in time. Also, an experiment in real cars could change the results and the obtained data. Participants can behave differently in the morning before a long day, than after work driving home after a long day. These effects would be important to take into account for further research.

The driving simulator consisted out of 14 drives which meant that a total time of almost 90 minutes was needed to complete all drivers including small breaks. The participants gave the feedback that this was about the maximum time they would like to spend in the driving simulator. Another reason for this can be that the scenarios were perceived as relatively similar, which made it hard for participants to notice any differences between the drives. This led to participants getting used to the road environment quickly, which was perceived as boring. However, all participants were able to finish the driving simulator experiment without experiencing any real discomfort.

Another important factor that has to be taken into account is that the car in which participants drove was not their own car. This could have caused difficulty in driving, which could have influenced the data. By doing a practice run the investigator tried to reduce this effect as much as possible. However, the simulator is not a real car, which could cause a slight deviation from normal driving behavior in a car. A frequent comment of the participants was that they found it hard to estimate how hard they were breaking based on only visual feedback. This may have influenced the THW during critical breaking actions.

Experimental design and driving behavior

Although great effort is made to create a realistic road environment and realistic driving behavior of surrounding traffic it cannot match reality. During the pilot tests it was found that all modelled vehicles had a strong preference to drive on the right lane. This resulted in congested situation on the right lane while the middle and left lane were unoccupied. In order to distribute the traffic more evenly over the lanes a number of countermeasures were taken. For all traffic the ability to make lane changes was restricted. 70% of traffic was randomly assigned and disabled to make a lane change. The selected vehicles were updated every 15s. Next to this, triggers were place on the right and middle lanes to induce lane changes made to the more left lanes. The manual adaptation of the lane changing behavior of the vehicles in the driving simulator resulted in a better distribution of traffic over the lanes. However, as a result, the lane changing behavior of surrounding traffic was sometimes perceived as mechanical and illogical. This could have affected the lane choice and lane changing behavior of the participants in the driving simulator.

Another factor which could have influenced the results is that the participants were given the same road section with the same speed strategy for all 14 drives. Due to a learning effect participants can already anticipate on upcoming situations since they knew what speed regulation was ahead on the road.

Data process and analysis

For the sake of simplicity, all indicators used in this research are either aggregated to averages or totals. Although this process is needed in order to investigate the behavior of a complete group, interesting information can be lost of overlooked.

The analysis of the driving style effect is dependent on the grouping method used to select the participants for the aggressive and social groups. In this research the Pro-social and Aggressive Driving Index questionnaire was used. The majority of the participants scored themselves as very social drivers. Nevertheless, the survey did result in interesting differences between participants and two groups could be made based on the driving index score. However, once the participants of the two groups were compared based on their driving behavior in the driving simulator no significant results were found. It can be that it is hard for humans to self asses their driving behavior, which means that their real-world driving behavior does not match their self-reported driving style. This means that using a self-reported driving behavior index is not a good method to create groups based on driving style. Besides, a bias can be created by the selection procedure of this experiment. It can be that social drivers are more prone to participate in a driving simulator experiment compared to aggressive drivers. This results in less distinct differences in driving behavior in the participants sample and does not lead to a good representation of the complete drivers population.

9. Recommendations

Both the scientific community and the transport sector benefit from a better understanding of behavioral adaptation of human drivers in mixed traffic. Below, recommendations for future research and practical recommendations are presented.

9.1 Recommendations for future research

- Future studies which make use of microscopic models should incorporate the behavioral adaptation of human drivers when modelling mixed traffic in combination with VSL to get more realistic insight into the traffic safety and efficiency.
- The same research could be conducted for varying levels of traffic density to see if the same behavioral adaptation is observed in more or less dense traffic flows.
- More levels for both penetration rate and upstream information could be included in this study. This would give more insight into the relation between the variables and the behavioral adaptation.
- To overcome the learning effect of participants on the upcoming speed limit, the speed limit profiles could be designed with more variability.
- The data of this research could be analyzed on a more disaggregated level. This gives more insight into the individual behavioral patterns and the effect of mixed traffic and VSL for specific individuals and driving styles.
- Multiple grouping variables can be chosen to investigate potential differences between specific groups other than driving style group. Interesting grouping variables could be age, gender, driving experience, ACC users and groups based on the subjective pleasantness of the ACC and VSL technologies. Disaggregated information on objective driving style could be used as well.
- Another factor often researched in mixed traffic is the recognizability of AVs. It would be interesting to see if the behavioral adaptation changes when CAVs become recognizable in mixed traffic in combination with VSL.
- A driving simulator study only gives insight in the potential behavioral adaptations. In order to quantify the real world effect, this study has to be extended with multiple field tests.
- It would be interesting to research what the effect would be if HDV drivers are provided with the same information as CAVs while still being able to make their own driving choices. It could be possible that even larger effects on speed compliance are observed if drivers know that a speed reduction is coming and thus know the reason for the decelerating behavior of surrounding vehicles.
- The application of connectivity with the infrastructure could be analyzed in a context where HDV drivers are provided with upstream information as well. For example with the help of in-vehicle devices.

9.2 Practical recommendations

- A large distance of upstream information (900m) should be considered when the goal is to influence the behavior of surrounding traffic by CAVs.
- In order for the communication to work, a cooperation is needed between road authorities and car manufactures. Therefore, a standardized communication technology should be decided on.
- To ensure a sufficient penetration rate of CAV the automotive industry has to be mandated to include the communication technology in the vehicles which are equipped with an ACC functionality.

- Additional thought is needed on how to stimulate drivers to make use of CAVs with upstream information. The incentive for CAV drivers is not obvious because they are the ones that are impacted most by reduced speed limits. Potential incentives could be road tax reductions or a discount on car insurance.
- A more in depth study should be executed in order to find the right distance of upstream information to CAVs to influence the behavior of HDV drivers for specific road environments. It could be that slowing down from 130kmph to 90kmph requires a different distance than slowing down from 70kmph to 50kmph.
- Communicating the speed limit to part of the traffic could be expanded to other use-cases on the road. Potential examples are roadblocks or road construction sites with reduced speed limits, and coordination of speed limits to prevent or suppress shock waves on motorways.

References

Aarts, L., & van Schagen, I. (2006, March). Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention*, *38*(2), 215–224. Retrieved 2021-08-13, from https://www.sciencedirect.com/science/article/pii/S0001457505001247 doi: 10.1016/j.aap.2005.07.004

Ali, Y., Sharma, A., Haque, M. M., Zheng, Z., & Saifuzzaman, M. (2020, September). The impact of the connected environment on driving behavior and safety: A driving simulator study. *Accident Analysis & Prevention*, *144*, 105643. Retrieved 2021-03-27, from https://www.sciencedirect.com/science/article/pii/S0001457520303092 doi: 10.1016/j.aap.2020.105643

Alkim, T. P., Bootsma, G., & Hoogendoorn, S. P. (2007, June). Field Operational Test "The Assisted Driver". In *2007 IEEE Intelligent Vehicles Symposium* (pp. 1198–1203). (ISSN: 1931-0587) doi: 10.1109/IVS.2007.4290281

Ardeshiri, A., & Jeihani, M. (2014, December). A speed limit compliance model for dynamic speed display sign. *Journal of Safety Research*, *51*, 33–40. Retrieved 2021-09-02, from https://www.sciencedirect.com/science/article/pii/S0022437514000863 doi: 10.1016/j.jsr.2014.08.001

Aria, E., Olstam, J., & Schwietering, C. (2016, January). Investigation of Automated Vehicle Effects on Driver's Behavior and Traffic Performance. *Transportation Research Procedia*, *15*, 761–770. Retrieved 2021-03-08, from https://www.sciencedirect.com/science/article/pii/S2352146516305968 doi: 10.1016/j.trpro.2016.06.063

Arthur, R. M. (2011, June). Examining Traffic Flow and Speed Data: Determining Imitative Behavior. *Traffic Injury Prevention*, *12*(3), 266–273. Retrieved 2021-09-06, from https://doi.org/10.1080/15389588.2011.555887 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15389588.2011.555887) doi: 10.1080/15389588.2011.555887

Ayres, T., Li, L., Schleuning, D., & Douglas, Y. (2001, February). Preferred time-headway of highway drivers. In (pp. 826–829). doi: 10.1109/ITSC.2001.948767

Beemster, F., Wilmink, I., & Taale, H. (2017). *Vervanging wegkantsystemen door incarsystemen: Een quick scan analyse* (Tech. Rep.). Delft: TrafficQuest. Retrieved from http://resolver.tudelft.nl/uuid:a55fef40-51f7-4aa1-8303-fc158abce7cf

Beza, A. D., & Zefreh, M. M. (2019, June). Potential Effects of Automated Vehicles on Road Transportation: A Literature Review. *Transport and Telecommunication Journal*, *20*(3), 269–278. Retrieved 2021-03-02, from https://content.sciendo.com/view/journals/ttj/20/3/article-p269.xml (Publisher: Sciendo Section: Transport and Telecommunication Journal) doi: 10.2478/ttj-2019-0023

Boyle, L. N., & Mannering, F. (2004, February). Impact of traveler advisory systems on driving speed: some new evidence. *Transportation Research Part C: Emerging Technologies*, *12*(1), 57–72. Retrieved 2021-08-16, from https://www.sciencedirect.com/science/article/pii/S0968090X03000779 doi: 10.1016/j.trc.2003.09.001

Brackstone, M., Waterson, B., & McDonald, M. (2009, March). Determinants of following headway in congested traffic. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(2), 131–142. Retrieved 2021-08-20, from https://www.sciencedirect.com/science/article/pii/S1369847808000867 doi: 10.1016/j.trf.2008.09.003

Böhm, M., Pfliegl, R., & Frötscher, A. (2008, January). Wireless Infrastructure-to-Vehicle Communication Technologies to Increase Road Safety along Motorways. *Transportation Research Record*, *2086*(1), 100–106. Retrieved 2021-08-19, from https://doi.org/10.3141/2086-12 (Publisher: SAGE Publications Inc) doi: 10.3141/2086-12

Carreras, A., Daura, X., Erhart, J., & Ruehrup, S. (2018, September). Road infrastructure support levels for automated driving. In (Vol. EU-TP1488). Copenhagen, Denmark. Retrieved from https://www.inframix.eu/wp-content/uploads/ITSWC2018-ASF-AAE-Final-paper_v4.pdf

Carsten, O., & Jamson, A. H. (2011, January). Chapter 7 - Driving Simulators as Research Tools in Traffic Psychology. In B. E. Porter (Ed.), *Handbook of Traffic Psychology* (pp. 87–96). San Diego: Academic Press. Retrieved 2021-03-27, from https://www.sciencedirect.com/science/article/pii/B9780123819840100074 doi: 10.1016/B978-0-12-381984-0.10007-4

Charlton, S. G., & Starkey, N. J. (2013, July). Driving on familiar roads: Automaticity and inattention blindness. *Transportation Research Part F: Traffic Psychology and Behaviour*, *19*, 121–133. Retrieved 2021-08-17, from https://www.sciencedirect.com/science/article/pii/S1369847813000326 doi: 10.1016/j.trf.2013.03.008

Cochran, W. (1963). *Sampling Techniques, 2*. New York: Aufl. John Wiley and Sons.

Connolly, T., & Åberg, L. (1993, February). Some contagion models of speeding. *Accident Analysis & Prevention*, *25*(1), 57–66. Retrieved 2021-09-06, from https://www.sciencedirect.com/science/article/pii/000145759390096F doi: 10.1016/0001-4575(93)90096-F

Davidse, R., Louwerse, W., & Duijvenvoorde, K. v. (2019). *Dodelijke verkeersongevallen op rijkswegen in 2017 - Analyse van ongevals- en letselfactoren en daaruit volgende aanknopingspunten voor maatregelen.* (Tech. Rep. No. R-2019-8). Den Haag: SWOV.

Davis, G., & Swenson, T. (2006, August). Collective responsibility for freeway rear-ending accidents?. An application of probabilistic causal models. *Accident; analysis and prevention*, *38*, 728–36. doi: 10.1016/j.aap.2006.01.003

Department for Transport. (2021, July). *Vehicle Speed Compliance Statistics: Methodology, Notes and Definitions* (Tech. Rep.). Retrieved 2021-08-12, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1001237/vehicle-speed-compliance-methodology-notes-definitions.pdf

Desimone, R., & Duncan, J. (1995). Neural Mechanisms of Selective Visual Attention. *Annual Review of Neuroscience*, *18*(1), 193–222. Retrieved 2021-09-15, from https://doi.org/10.1146/annurev.ne.18.030195.001205 (_eprint: https://doi.org/10.1146/annurev.ne.18.030195.001205) doi: 10.1146/annurev.ne.18.030195.001205

D. Frejo, J. R., Papamichail, I., Papageorgiou, M., & De Schutter, B. (2019, March). Macroscopic modeling of variable speed limits on freeways. *Transportation Research Part C: Emerging Technologies*, *100*, 15–33. Retrieved 2021-08-12, from https://www.sciencedirect.com/science/article/pii/S0968090X18303310 doi: 10.1016/j.trc.2019.01.001

Dollard, J., Doob, W., Miller, N., Mowrer, O., & Sears, R. (1939). *Frustration and aggression*. New Haven: CT: Yale University PRess.

Eiermann, L., Sawade, O., Bunk, S., Breuel, G., & Radusch, I. (2020, October). Co-operative automated lane merge with role-based negotiation. In *2020 IEEE Intelligent Vehicles Symposium (IV)* (pp. 495–501). (ISSN: 2642-7214) doi: 10.1109/IV47402.2020.9304711

European Parlement. (2019, November). *Regulation (EU) 2019/2144*. Retrieved 2021-08-20, from https://eur-lex.europa.eu/eli/reg/2019/2144/oj

Fifer, S., Rose, J., & Greaves, S. (2014, March). Hypothetical bias in Stated Choice Experiments: Is it a problem? And if so, how do we deal with it? *Transportation Research Part A: Policy and Practice*, *61*, 164–177. Retrieved 2021-08-25, from https://www.sciencedirect.com/science/article/pii/S0965856413002486 doi: 10.1016/j.tra.2013.12.010

Goldenbeld, C., & van Schagen, I. (2007, November). The credibility of speed limits on 80km/h rural roads: The effects of road and person(ality) characteristics. *Accident Analysis & Prevention*, *39*(6), 1121–1130. Retrieved 2021-08-12, from https://www.sciencedirect.com/science/article/pii/S0001457507000292 doi: 10.1016/j.aap.2007.02.012

Golob, T. F., Recker, W. W., & Alvarez, V. M. (2004, November). Freeway safety as a function of traffic flow. *Accident Analysis & Prevention*, *36*(6), 933–946. Retrieved 2021-08-11, from https://www.sciencedirect.com/science/article/pii/S0001457503001520 doi: 10.1016/j.aap.2003.09.006

Gouy, M. (2013). Behavioural adaption of drivers of unequipped vehicles to short time headways observed in a vehicle platoon. *undefined*, 185. Retrieved 2021-08-10, from https://www.semanticscholar.org/paper/Behavioural-adaption-of-drivers-of-unequipped-to-in-Gouy/68fa9e0a124791d33ff5434e0e7641cb867498f6 doi: 10.21954/ou.ro.00009d8f

Gouy, M., Wiedemann, K., Stevens, A., Brunett, G., & Reed, N. (2014, November). Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control? *Transportation Research Part F: Traffic Psychology and Behaviour*, *27*, 264–273. Retrieved 2021-03-08, from https://www.sciencedirect.com/science/article/pii/S1369847814000345 doi: 10.1016/j.trf.2014.03.003

Grumert, E. F., Tapani, A., & Ma, X. (2018, May). Characteristics of variable speed limit systems. *European Transport Research Review*, *10*(2), 21. Retrieved 2021-05-29, from https://doi.org/10.1186/s12544-018-0294-8 doi: 10.1186/s12544-018-0294-8

Guerrero-Ibáñez, J., Zeadally, S., & Contreras-Castillo, J. (2018, April). Sensor Technologies for Intelligent Transportation Systems. *Sensors*, *18*(4), 1212. Retrieved 2021-08-03, from https://www.mdpi.com/1424-8220/18/4/1212 (Number: 4 Publisher: Multidisciplinary Digital Publishing Institute) doi: 10.3390/s18041212

Guo, M., Wu, Z., & Zhu, H. (2018, January). Empirical study of lane-changing behavior on three Chinese freeways. *PLOS ONE*, *13*(1), e0191466. Retrieved 2021-08-12, from https://dx.plos.org/10.1371/journal.pone.0191466 doi: 10.1371/journal.pone.0191466

Guo, X., Jiang, Y., & Kim, I. (2020, April). Interacting with Autonomous Platoons: Human Driver's Adaptive Behaviors in Planned Lane Changes. In *2020 Systems and Information Engineering Design Symposium (SIEDS)* (pp. 1–5). doi: 10.1109/SIEDS49339.2020.9106667

Han, Y., Chen, D., & Ahn, S. (2017, April). Variable speed limit control at fixed freeway bottlenecks using connected vehicles. *Transportation Research Part B: Methodological*, *98*, 113–134. Retrieved 2022-02-05, from https://www.sciencedirect.com/science/article/pii/S0191261516303964 doi: 10.1016/j.trb.2016.12.013

Harms, I. M., & Brookhuis, K. A. (2016, April). Dynamic traffic management on a familiar road: Failing to detect changes in variable speed limits. *Transportation Research Part F: Traffic Psychology and Behaviour*, *38*, 37–46. Retrieved 2021-08-09, from https://www.sciencedirect.com/science/article/pii/S1369847816000061 doi: 10.1016/j.trf.2016.01.005

Harris, P. B., Houston, J. M., Vazquez, J. A., Smither, J. A., Harms, A., Dahlke, J. A., & Sachau, D. A. (2014, November). The Prosocial and Aggressive Driving Inventory (PADI): A self-report measure of safe and unsafe driving behaviors. *Accident Analysis & Prevention*, *72*, 1–8. Retrieved 2021-09-15, from https://www.sciencedirect.com/science/article/pii/S0001457514001651 doi: 10.1016/j.aap.2014.05.023

Hegyi, A., Schutter, B. D., & Hellendoorn, J. (2005, March). Optimal coordination of variable speed limits to suppress shock waves. *IEEE Transactions on Intelligent Transportation Systems*, *6*(1), 102–112. (Conference Name: IEEE Transactions on Intelligent Transportation Systems) doi: 10.1109/TITS.2004.842408

Hellinga, B., & Mandelzys, M. (2011, April). Impact of Driver Compliance on the Safety and Operational Impacts of Freeway Variable Speed Limit Systems. *Journal of Transportation Engineering*, *137*(4), 260–268. Retrieved 2021-06-18, from https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29TE.1943-5436.0000214 (Publisher: American Society of Civil Engineers) doi: 10.1061/(ASCE)TE.1943-5436.0000214

Hill, C., Elefteriadou, L., & Kondyli, A. (2014, November). Exploratory Analysis of Lane Changing on Freeways Based on Driver Behavior. *Journal of Transportation Engineering*, *141*. doi: 10.1061/(ASCE)TE.1943-5436.0000758

Hoferlin, B., & Zimmermann, K. (2009, June). Towards reliable traffic sign recognition. In *2009 IEEE Intelligent Vehicles Symposium* (pp. 324–329). (ISSN: 1931-0587) doi: 10.1109/IVS.2009.5164298

Hogema, J. H. (1999, January). Modeling Motorway Driving Behavior. *Transportation Research Record*, *1689*(1), 25–32. Retrieved 2022-01-17, from https://doi.org/10.3141/

1689-04 (Publisher: SAGE Publications Inc) doi: 10.3141/1689-04
Israel, G. (1992). *Determining sample size* (Tech. Rep. No. Fact Sheet PEOD-6). Gainesville: Univeristy of Florida.
Jallow, H., Renukappa, S., & Alneyadi, A. (2019, June). The Concept of Smart Motorways. In *2019 3rd International Conference on Smart Grid and Smart Cities (ICSGSC)* (pp. 18–21). doi: 10.1109/ICSGSC.2019.00-25
Jin, W.-L. (2013, June). A Multi-commodity Lighthill-Whitham-Richards Model of Lane-changing Traffic Flow. *Procedia - Social and Behavioral Sciences*, *80*, 658–677. Retrieved 2021-08-12, from https://www.sciencedirect.com/science/article/pii/S1877042813010045 doi: 10.1016/j.sbspro.2013.05.035
Johnson, M. B., & McKnight, S. (2009, July). Warning Drivers About Potential Congestion as a Means to Reduce Frustration-Driven Aggressive Driving. *Traffic Injury Prevention*, *10*(4), 354–360. Retrieved 2021-09-14, from https://doi.org/10.1080/15389580902969765 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15389580902969765) doi: 10.1080/15389580902969765
Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993, July). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*(3), 203–220. Retrieved 2021-09-17, from https://doi.org/10.1207/s15327108ijap0303_3 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1207/s15327108ijap0303_3) doi: 10.1207/s15327108ijap0303_3
Keyvan-Ekbatani, M., Knoop, V. L., & Daamen, W. (2016, August). Categorization of the lane change decision process on freeways. *Transportation Research Part C: Emerging Technologies*, *69*, 515–526. Retrieved 2021-08-12, from https://www.sciencedirect.com/science/article/pii/S0968090X1500412X doi: 10.1016/j.trc.2015.11.012
Khondaker, B., & Kattan, L. (2015a, September). Variable speed limit: A microscopic analysis in a connected vehicle environment. *Transportation Research Part C: Emerging Technologies*, *58*, 146–159. Retrieved 2021-10-08, from https://www.sciencedirect.com/science/article/pii/S0968090X15002648 doi: 10.1016/j.trc.2015.07.014
Khondaker, B., & Kattan, L. (2015b, October). Variable speed limit: an overview. *Transportation Letters*, *7*(5), 264–278. Retrieved 2021-10-08, from https://doi.org/10.1179/1942787514Y.0000000053 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1179/1942787514Y.0000000053) doi: 10.1179/1942787514Y.0000000053
Kim, H., Hwang, Y., Yoon, D., & Park, C. H. (2013, October). An analysis of driver's workload in the lane change behavior. In *2013 International Conference on ICT Convergence (ICTC)* (pp. 242–247). (ISSN: 2162-1241) doi: 10.1109/ICTC.2013.6675350
Kulmala, R., & Rämä, P. (2013). Definition of behavioural adaptation. In *Behavioural Adaptation and Road Safety: Theory, Evidence and Action* (pp. 11–22). Definition of behavioural adaptation. In: Behavioural Adaptation and Road Safety: Theory, Evidence and Action.
Kurzhanskiy, A. A., & Varaiya, P. (2010, June). Using Aurora Road Network Modeler for Active Traffic Management. In *Proceedings of the 2010 American Control Conference* (pp. 2260–2265). (ISSN: 2378-5861) doi: 10.1109/ACC.2010.5530532
Laval, J. A., & Daganzo, C. F. (2006, March). Lane-changing in traffic streams. *Transportation Research Part B: Methodological*, *40*(3), 251–264. Retrieved 2021-08-12, from https://www.sciencedirect.com/science/article/pii/S019126150500055X doi: 10.1016/j.trb.2005.04.003
Lee, C., & Abdel-Aty, M. (2008, January). Testing Effects of Warning Messages and Variable Speed Limits on Driver Behavior Using Driving Simulator. *Transportation Research Record*, *2069*(1), 55–64. Retrieved 2021-08-25, from https://doi.org/10.3141/2069-08 (Publisher: SAGE Publications Inc) doi: 10.3141/2069-08
Lee, S., & Oh, C. (2017). Lane Change Behavior of Manual Vehicles in Automated Vehicle Platooning Environments. *Journal of Korean Society of Transportation*, *35*(4), 332–347. Retrieved 2021-08-10, from https://www.koreascience.or.kr/article/JAKO201732863554971.page?&lang=en (Publisher: Korean Society of Transportation)

doi: 10.7470/jkst.2017.35.4.332
Lee, S., Oh, C., & Hong, S. (2018). Exploring lane change safety issues for manually driven vehicles in vehicle platooning environments. *IET Intelligent Transport Systems*, *12*(9), 1142–1147. Retrieved 2021-08-10, from https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-its.2018.5167 (_eprint: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/iet-its.2018.5167) doi: 10.1049/iet-its.2018.5167
Lees, M. N., & Lee, J. D. (2007, August). The influence of distraction and driving context on driver response to imperfect collision warning systems. *Ergonomics*, *50*(8), 1264–1286. Retrieved 2021-08-16, from https://doi.org/10.1080/00140130701318749 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00140130701318749) doi: 10.1080/00140130701318749
Li, Y., Wang, H., Wang, W., Liu, S., & Xiang, Y. (2016, August). Reducing the risk of rear-end collisions with infrastructure-to-vehicle (I2V) integration of variable speed limit control and adaptive cruise control system. *Traffic Injury Prevention*, *17*(6), 597–603. Retrieved 2021-08-11, from https://doi.org/10.1080/15389588.2015.1121384 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15389588.2015.1121384) doi: 10.1080/15389588.2015.1121384
Li, Z., Liu, P., Wang, W., & Xu, C. (2014, April). Development of a Control Strategy of Variable Speed Limits to Reduce Rear-End Collision Risks Near Freeway Recurrent Bottlenecks. *IEEE Transactions on Intelligent Transportation Systems*, *15*(2), 866–877. (Conference Name: IEEE Transactions on Intelligent Transportation Systems) doi: 10.1109/TITS.2013.2293199
Loulizi, A., Bichiou, Y., & Rakha, H. (2019, May). Steady-State Car-Following Time Gaps: An Empirical Study Using Naturalistic Driving Data. *Journal of Advanced Transportation*, *2019*, e7659496. Retrieved 2021-08-19, from https://www.hindawi.com/journals/jat/2019/7659496/ (Publisher: Hindawi) doi: 10.1155/2019/7659496
Mahdinia, I., Mohammadnazar, A., Arvin, R., & Khattak, A. (2021). Integration of automated vehicles in mixed traffic: Evaluating changes in performance of following human-driven vehicles. *Accident Analysis and Prevention*, *152*. doi: 10.1016/j.aap.2021.106006
Makridis, M., Mattas, K., Anesiadou, A., & Ciuffo, B. (2021, April). OpenACC. An open database of car-following experiments to study the properties of commercial ACC systems. *Transportation Research Part C: Emerging Technologies*, *125*, 103047. Retrieved 2021-08-19, from https://www.sciencedirect.com/science/article/pii/S0968090X21000772 doi: 10.1016/j.trc.2021.103047
Malikopoulos, A. A., Hong, S., Park, B. B., Lee, J., & Ryu, S. (2019, July). Optimal Control for Speed Harmonization of Automated Vehicles. *IEEE Transactions on Intelligent Transportation Systems*, *20*(7), 2405–2417. (Conference Name: IEEE Transactions on Intelligent Transportation Systems) doi: 10.1109/TITS.2018.2865561
Marczak, F., Daamen, W., & Buisson, C. (2013, June). Key Variables of Merging Behaviour: Empirical Comparison between Two Sites and Assessment of Gap Acceptance Theory. *Procedia - Social and Behavioral Sciences*, *80*, 678–697. Retrieved 2021-08-23, from https://www.sciencedirect.com/science/article/pii/S1877042813010057 doi: 10.1016/j.sbspro.2013.05.036
Martens, M. (2013). Behavioural adaptation to roadway intelligent transport systems. In C. Rudin-Brown & S. Jamson (Eds.), *Behavioural Adaptation and Road Safety: Theory, Evidence and Action* (pp. 135–160). New York: CRC Press.
Matowicki, M., & Pribyl, O. (2021, May). A driving simulation study on drivers speed compliance with respect to variable message signs. *Journal of Intelligent Transportation Systems*, 1–11. Retrieved 2021-06-01, from https://www.tandfonline.com/doi/full/10.1080/15472450.2021.1926247 doi: 10.1080/15472450.2021.1926247
Mehmood, A., & Easa, S. M. (2009). Modeling reaction time in car-following behaviour based on human factors. *International Journal of Applied Science, Engineering and Technology*(33), 710–718.
Middelham, F. (2003, August). State of Practice in Dynamic Traffic Management in the

Netherlands. *IFAC Proceedings Volumes*, *36*(14), 293–298. Retrieved 2021-10-21, from https://www.sciencedirect.com/science/article/pii/S1474667017324357 doi: 10.1016/S1474-6670(17)32435-7

Milakis, D., Snelder, M., Arem, B. v., Wee, B. v., & Correia, G. H. d. A. (2017, January). Development and transport implications of automated vehicles in the Netherlands: scenarios for 2030 and 2050. *European Journal of Transport and Infrastructure Research*, *17*(1). Retrieved 2021-03-03, from https://journals.open.tudelft.nl/ejtir/article/view/3180 doi: 10.18757/ejtir.2017.17.1.3180

Mohammadi, S., Arvin, R., Khattak, A. J., & Chakraborty, S. (2021, July). The role of drivers' social interactions in their driving behavior: Empirical evidence and implications for car-following and traffic flow. *Transportation Research Part F: Traffic Psychology and Behaviour*, *80*, 203–217. Retrieved 2021-09-06, from https://www.sciencedirect.com/science/article/pii/S1369847821000838 doi: 10.1016/j.trf.2021.04.002

Moridpour, S. (2014). Evaluating the Time Headway Distributions in Congested Highways. *Journal of Traffic and Logistics Engineering*, *2*(3). Retrieved 2021-08-19, from http://www.jtle.net/index.php?m=content&c=index&a=show&catid=36&id=105 doi: 10.12720/jtle.2.3.224-229

Naujoks, F., & Totzke, I. (2014, September). Behavioral adaptation caused by predictive warning systems – The case of congestion tail warnings. *Transportation Research Part F: Traffic Psychology and Behaviour*, *26*, 49–61. Retrieved 2021-09-02, from https://www.sciencedirect.com/science/article/pii/S1369847814000849 doi: 10.1016/j.trf.2014.06.010

OECD/ECMT. (2006). *Speed Management*. Paris.

Olia, A., Abdelgawad, H., Abdulhai, B., & Razavi, S. N. (2016, May). Assessing the Potential Impacts of Connected Vehicles: Mobility, Environmental, and Safety Perspectives. *Journal of Intelligent Transportation Systems*, *20*(3), 229–243. Retrieved 2021-03-09, from https://doi.org/10.1080/15472450.2015.1062728 (Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15472450.2015.1062728) doi: 10.1080/15472450.2015.1062728

Pan, T., Guo, R., Lam, W. H. K., Zhong, R., Wang, W., & He, B. (2021, February). Integrated optimal control strategies for freeway traffic mixed with connected automated vehicles: A model-based reinforcement learning approach. *Transportation Research Part C: Emerging Technologies*, *123*(102987). Retrieved 2021-05-20, from https://www.sciencedirect.com/science/article/pii/S0968090X2100022X doi: 10.1016/j.trc.2021.102987

Papageorgiou, M., Kosmatopoulos, E., & Papamichail, I. (2008, January). Effects of Variable Speed Limits on Motorway Traffic Flow. *Transportation Research Record*, *2047*(1), 37–48. Retrieved 2021-09-08, from https://doi.org/10.3141/2047-05 (Publisher: SAGE Publications Inc) doi: 10.3141/2047-05

Pype, P., Daalderop, G., Schulz-Kamm, E., Walters, E., Blom, G., & Westermann, S. (2017). Intelligent Transport Systems: The Trials Making Smart Mobility a Reality. In D. Watzenig & M. Horn (Eds.), *Automated Driving: Safer and More Efficient Future Driving* (pp. 595–600). Cham: Springer International Publishing. Retrieved 2021-09-10, from https://doi.org/10.1007/978-3-319-31895-0_30 doi: 10.1007/978-3-319-31895-0_30

Qi, X., Sun, T., Ma, W., Wang, L., & Yu, C. (2020). Evaluation of a variable speed limit system using a hierarchical framework under a connected vehicles environment: a case study of a field test in Seattle. *IET Intelligent Transport Systems*, *14*(9), 1125–1131. Retrieved 2021-05-28, from https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-its.2019.0858 (_eprint: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/iet-its.2019.0858) doi: https://doi.org/10.1049/iet-its.2019.0858

Rahmati, Y., Khajeh Hosseini, M., Talebpour, A., Swain, B., & Nelson, C. (2019, December). Influence of Autonomous Vehicles on Car-Following Behavior of Human Drivers. *Transportation Research Record*, *2673*(12), 367–379. Retrieved 2021-03-08, from https://doi.org/10.1177/0361198119862628 (Publisher: SAGE Publications

Inc) doi: 10.1177/0361198119862628

Reason, J., Manstead, A., Stradling, S., Baxter, J., & Campbell, K. (1990, October). Errors and violations on the roads: a real distinction? *Ergonomics*, *33*(10-11), 1315–1332. Retrieved 2021-09-16, from http://www.tandfonline.com/doi/abs/10.1080/00140139008925335 doi: 10.1080/00140139008925335

Rijkswaterstaat Water, Verkeer en Leefomgeving. (2020, March). *Veilig over Rijkswegen 2019 : monitoringsrapport verkeersveiligheid van rijkswegen : deel A: landelijk beeld* (Tech. Rep. No. PUC_640042_31). Rijkswaterstaat. Retrieved 2021-09-03, from https://puc.overheid.nl/doc/PUC_640042_31

Risto, M., & Martens, M. H. (2013, February). Time and space: The difference between following time headway and distance headway instructions. *Transportation Research Part F: Traffic Psychology and Behaviour*, *17*, 45–51. Retrieved 2021-12-17, from https://www.sciencedirect.com/science/article/pii/S1369847812000964 doi: 10.1016/j.trf.2012.09.004

SAE. (2015, June). *Operational Definitions of Driving Performance Measures and Statistics* (Tech. Rep.). SAE International. Retrieved from https://www.sae.org/standards/content/j2944_201506/

SAE. (2021a, July). *Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles* (Tech. Rep.). Retrieved from https://saemobilus.sae.org/content/j3216_202107

SAE. (2021b, April). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (Tech. Rep.). Retrieved from https://www.sae.org/standards/content/j3016_202104/

Sagberg, F., Fosser, S., & Sætermo, I.-A. F. (1997, May). An investigation of behavioural adaptation to airbags and antilock brakes among taxi drivers. *Accident Analysis & Prevention*, *29*(3), 293–302. Retrieved 2021-09-02, from https://www.sciencedirect.com/science/article/pii/S0001457596000838 doi: 10.1016/S0001-4575(96)00083-8

Sanguesa, J. A., Barrachina, J., Fogue, M., Garrido, P., Martinez, F. J., Cano, J.-C., ... Manzoni, P. (2015, December). Sensing Traffic Density Combining V2V and V2I Wireless Communications. *Sensors*, *15*(12), 31794–31810. Retrieved 2021-03-08, from https://www.mdpi.com/1424-8220/15/12/29889 (Number: 12 Publisher: Multidisciplinary Digital Publishing Institute) doi: 10.3390/s151229889

Schelling, I., Hegyi, A., & Hoogendoorn, S. P. (2011, October). SPECIALIST-RM — Integrated variable speed limit control and ramp metering based on shock wave theory. In *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)* (pp. 2154–2159). (ISSN: 2153-0017) doi: 10.1109/ITSC.2011.6083116

Schoenmakers, M., Yang, D., & Farah, H. (2021, April). Car-following behavioural adaptation when driving next to automated vehicles on a dedicated lane on motorways: A driving simulator study in the Netherlands. *Transportation Research Part F: Traffic Psychology and Behaviour*, *78*, 119–129. Retrieved 2021-05-14, from https://www.sciencedirect.com/science/article/pii/S1369847821000176 doi: 10.1016/j.trf.2021.01.010

Sharma, A., Ali, Y., Saifuzzaman, M., Zheng, Z., & Haque, M. M. (2018). Human Factors in Modelling Mixed Traffic of Traditional, Connected, and Automated Vehicles. In D. N. Cassenti (Ed.), *Advances in Human Factors in Simulation and Modeling* (pp. 262–273). Cham: Springer International Publishing. doi: 10.1007/978-3-319-60591-3_24

Sharma, A., Zheng, Z., Bhaskar, A., & Haque, M. M. (2019, August). Modelling car-following behaviour of connected vehicles with a focus on driver compliance. *Transportation Research Part B: Methodological*, *126*, 256–279. Retrieved 2021-03-11, from https://www.sciencedirect.com/science/article/pii/S0191261518306362 doi: 10.1016/j.trb.2019.06.008

Sharma, A., Zheng, Z., Kim, J., Bhaskar, A., & Mazharul Haque, M. (2021, March). Assessing traffic disturbance, efficiency, and safety of the mixed traffic flow of connected vehicles and traditional vehicles by considering human factors. *Transportation Research Part C: Emerging Technologies*, *124*, 102934. Retrieved 2021-03-05, from https://www.sciencedirect.com/science/article/pii/S0968090X20308329 doi: 10.1016/j.trc.2020.102934

Smiley, A. (2000, January). Behavioral Adaptation, Safety, and Intelligent Transportation Systems. *Transportation Research Record*, *1724*(1), 47–51. Retrieved 2021-03-10, from https://doi.org/10.3141/1724-07 (Publisher: SAGE Publications Inc) doi: 10.3141/1724-07

Soole, D. W., Watson, B. C., & Fleiter, J. J. (2013, May). Effects of average speed enforcement on speed compliance and crashes: A review of the literature. *Accident Analysis & Prevention*, *54*, 46–56. Retrieved 2021-08-13, from https://www.sciencedirect.com/science/article/pii/S0001457513000432 doi: 10.1016/j.aap.2013.01.018

Strömgren, P., & Lind, G. (2016, January). Harmonization with Variable Speed Limits on Motorways. *Transportation Research Procedia*, *15*, 664–675. Retrieved 2021-05-29, from https://www.sciencedirect.com/science/article/pii/S2352146516305889 doi: 10.1016/j.trpro.2016.06.056

SWOV. (2013). *Headway times and road safety* (Tech. Rep.). The Hagaue, The Netherlands: Author.

SWOV. (2020). Kosten van verkeersongevallen. *SWOV-Factsheet, Maart 2020*. (Place: Den Haag Publisher: SWOV)

Taubman-Ben-Ari, O., Mikulincer, M., & Gillath, O. (2004, May). The multidimensional driving style inventory—scale construct and validation. *Accident Analysis & Prevention*, *36*(3), 323–332. Retrieved 2021-09-16, from https://www.sciencedirect.com/science/article/pii/S0001457503000101 doi: 10.1016/S0001-4575(03)00010-1

Teh, E. T. T., Jamson, S., & Carsten, O. (2012). How Does a Lane Change Performed by a Neighbouring Vehicle Affect Driver Workload?. Retrieved 2021-08-12, from https://trid.trb.org/view/1261310

TRB. (2010). *Highway capacity manual 2010, Volumes 1-4*. Washington, DC: Transportation Research Board.

Van Der Laan, J. D., Heino, A., & De Waard, D. (1997, February). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research Part C: Emerging Technologies*, *5*(1), 1–10. Retrieved 2021-09-17, from https://www.sciencedirect.com/science/article/pii/S0968090X96000253 doi: 10.1016/S0968-090X(96)00025-3

van Huysduynen, H. H., Terken, J., & Eggen, B. (2018, July). The relation between self-reported driving style and driving behaviour. A simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *56*, 245–255. Retrieved 2021-08-25, from https://www.sciencedirect.com/science/article/pii/S1369847817300682 doi: 10.1016/j.trf.2018.04.017

van Nes, N., Brandenburg, S., & Twisk, D. (2010, May). Improving homogeneity by dynamic speed limit systems. *Accident Analysis & Prevention*, *42*(3), 944–952. Retrieved 2021-03-06, from https://www.sciencedirect.com/science/article/pii/S0001457509000992 doi: 10.1016/j.aap.2009.05.002

Varotto, S. F., Jansen, R., Bijleveld, F., & van Nes, N. (2021a, April). Adaptations in driver deceleration behaviour with automatic incident detection: A naturalistic driving study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *78*, 164–179. Retrieved 2021-08-25, from https://www.sciencedirect.com/science/article/pii/S1369847821000358 doi: 10.1016/j.trf.2021.02.011

Varotto, S. F., Jansen, R., Bijleveld, F., & van Nes, N. (2021b, February). Driver speed compliance following automatic incident detection: Insights from a naturalistic driving study. *Accident Analysis & Prevention*, *150*, 105939. Retrieved 2021-08-16, from https://www.sciencedirect.com/science/article/pii/S0001457520317590 doi: 10.1016/j.aap.2020.105939

Vogel, K. (2002, March). What characterizes a "free vehicle" in an urban area? *Transportation Research Part F: Traffic Psychology and Behaviour*, *5*(1), 15–29. Retrieved 2021-08-11, from https://www.sciencedirect.com/science/article/pii/S1369847802000037 doi: 10.1016/S1369-8478(02)00003-7

Wang, K., Liu, H., Zeng, J., Niu, C., Cao, F., & Ji, J. (2020, December). Analysis and

Prevention of Chain Collision in Traditional and Connected Vehicular Platoon. In *2020 4th CAA International Conference on Vehicular Control and Intelligence (CVCI)* (pp. 726–730). doi: 10.1109/CVCI51460.2020.9338496

Williams, B. (2008). *Intelligent Transport Systems Standards*. Artech House. (Google-Books-ID: RUI279GxpEkC)

Witmer, B. G., & Singer, M. J. (1998, June). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, *7*(3), 225–240. Retrieved 2021-09-17, from https://doi.org/10.1162/105474698565686 doi: 10.1162/105474698565686

Wu, K.-F., & Thor, C. P. (2015, January). Method for the Use of Naturalistic Driving Study Data to Analyze Rear-End Crash Sequences. *Transportation Research Record*, *2518*(1), 27–36. Retrieved 2021-08-11, from https://doi.org/10.3141/2518-04 (Publisher: SAGE Publications Inc) doi: 10.3141/2518-04

Yang, D., Farah, H., Schoenmakers, M. J., & Alkim, T. (2019). Human drivers behavioural adaptation when driving next to a platoon of automated vehicles on a dedicated lane and implications on ttraffic flow: a driving simulator and microscopic simulation study in the Netherlands. In *Proceedings 98th Annual Meeting of the Transportation Research Board, Washington DC, USA* (p. 19). Retrieved 2021-08-10, from https://research.tue.nl/en/publications/human-drivers-behavioural-adaptation-when-driving-next-to-a-plato

Yao, Y., Carsten, O., & Hibberd, D. (2020, September). Predicting Compliance with Speed Limits using Speed Limit Credibility Perception and Risk Perception Data. *Transportation Research Record*, *2674*(9), 450–461. Retrieved 2021-08-13, from https://doi.org/10.1177/0361198120929696 (Publisher: SAGE Publications Inc) doi: 10.1177/0361198120929696

Zegeye, S. K., De Schutter, B., Hellendoorn, J., & Breunesse, E. A. (2010, September). Variable speed limits for area-wide reduction of emissions. In *13th International IEEE Conference on Intelligent Transportation Systems* (pp. 507–512). (ISSN: 2153-0017) doi: 10.1109/ITSC.2010.5625032

Zhao, X., Wang, Z., Xu, Z., Wang, Y., Li, X., & Qu, X. (2020, May). Field experiments on longitudinal characteristics of human driver behavior following an autonomous vehicle. *Transportation Research Part C: Emerging Technologies*, *114*, 205–224. Retrieved 2021-08-10, from https://www.sciencedirect.com/science/article/pii/S0968090X18313767 doi: 10.1016/j.trc.2020.02.018

Zhong, Z., Lee, E. E., Nejad, M., & Lee, J. (2020, June). Influence of CAV clustering strategies on mixed traffic flow characteristics: An analysis of vehicle trajectory data. *Transportation Research Part C: Emerging Technologies*, *115*, 102611. Retrieved 2021-03-09, from https://www.sciencedirect.com/science/article/pii/S0968090X19307648 doi: 10.1016/j.trc.2020.102611

Ziebinski, A., Cupek, R., Grzechca, D., & Chruszczyk, L. (2017, November). Review of advanced driver assistance systems (ADAS). *AIP Conference Proceedings 1906*, *120002*(1). Retrieved 2021-09-10, from https://aip.scitation.org/doi/abs/10.1063/1.5012394 (Publisher: American Institute of Physics) doi: 10.1063/1.5012394

Özkan, T., Lajunen, T., Parker, D., Sümer, N., & Summala, H. (2010, June). Symmetric Relationship Between Self and Others in Aggressive Driving Across Gender and Countries. *Traffic Injury Prevention*, *11*(3), 228–239. doi: 10.1080/15389581003788864

A. Scientific paper

Driving behavior in mixed traffic in combination with variable speed limit

Jitse Wiersma
MSc Transport, Infrastructure and Logistics
Technical University Delft, The Netherlands

Abstract – New applications of connectivity between vehicles and the infrastructure are developed. One of these applications is providing upstream information on variable speed limits to connected and automated vehicles. It is expected that the connectivity can contribute to safer roads due to better compliance to the posted speed limits. Those expectations are based on microscopic models with the assumption that human drivers behave similarly in mixed traffic as they do in only human driven vehicles traffic. However, few studies have shown that human drivers tend to change their driving behavior when interacting with automated vehicles in mixed traffic. For this reason, a driving simulator experiment is executed to investigate the effect of the penetration rate of connected and automated vehicles and the distance at which the information is provided on the driving behavior of human drivers. The driving behavior was analyzed in terms of longitudinal and lateral behavior in the context of a three-lane motorway. The penetration rate was found to only impact the speed adaptation when combined with a large distance of upstream information. Lower means speeds, lower section entry speeds and increased speed compliance was observed with an increasing level of penetration rate. For the effect of distance of upstream information, a similar effect was observed. When the distance was increased the mean speed lowered, section entry speed lowered, and speed compliance increased. No change was observed regarding the lateral behavior or Time Headway. As a result, it can be concluded that the cooperation between connected and automated vehicles and variable speed limits on motorways can be used to slow down unconnected vehicles more upstream, without inducing aggressive driving behavior in terms Time Headway and lane changing behavior.

Keywords – Mixed traffic, Behavioral adaptation, Variable speed limit, Upstream information, Driving simulator

1. Introduction.

Vehicles are under constant development, resulting in new forms of Advanced Driver Assistance Systems (ADAS) and (partly) automated driving. Developments in vehicle technology are generally introduced to either improve the driving experience or make driving safer.

With the introduction of more automated vehicles on public roads a new type of vehicle is combined with human driven vehicles (HDV). Despite automated vehicles promise to take over the driving task completely, HDVs will be predominantly existing on public roads in the coming years [1]. The combination of both vehicle types operating in the same traffic environment is called mixed traffic.

A potential application of AVs is the cooperation between vehicles and the infrastructure with the help of communication technologies. Multiple studies promise a benefit in both traffic safety and efficiency by cooperative automated vehicles (CAVs) connected to the infrastructure [2]–[4].

In this research a specific application of cooperation between AVs and the infrastructure is chosen. The application is the cooperation between Variable Speed Limits (VSLs) and CAVs. VSL is a widely used technique that allows for flexible, remote, and manual or automatic adaptation of speed limits [5]. Several types of VSL systems are implemented around the globe with different objectives and type of operations. The main goal of VSL is to improve traffic safety and flow by increasing homogeneity of traffic and reducing speed violations [6].

The cooperation and simultaneous application of VSL and CAVs could lead to further improvements in traffic safety and efficiency if the speed limit is communicated more upstream to CAVs. It is expected that introducing slower vehicles by providing upstream information to connected vehicles will slow down the other part of the traffic as well [2], [7].

Most of the studies make use of microscopic models to analyze the effect of communication technologies in mixed traffic [8]. However, most microscopic models do not incorporate behavioral adaptation of HDV drivers in mixed traffic.

Previous literature on mixed traffic has found that human drivers tend to change their driving behavior when interacting with (partly) automated vehicles (AVs) on the road compared to when interacting with HDVs [9]–[11]. Human drivers tend to copy shorter Time Headways (THWs) next to AV platoons [9] and keep shorter THW when following an AV [10]. Besides, human drivers who follow an AV show lower driving volatility in terms of speed and acceleration [12]. Moreover, an increased penetration rate of AVs results in larger lane change preparation time [13] and longer lane change duration [14].

Motorway driving behavior can be described by three sub behaviors, car-following, lane-changing and speed adaptation behavior [15].

Although few insights in the behavioral adaptation of human drivers in mixed traffic are researched still a lot is unknown.

To have realistic insights into the benefits of the cooperation between VSL and, CAV a better understanding of the potential change in driving behavior of HDV drivers is needed. An improved understanding will contribute to better microscopic models and thus lead to more realistic results. Moreover, if behavioral adaption is understood, countermeasures can be examined to overcome negative effects on traffic safety and flow. Therefore, the main question of this research is: ***How do human drivers change their car-following, lane-changing and speed adaptation behavior in mixed traffic in combination with VSL on motorways?***

The focus of this research is the effect of the presence of CAVs in combination with upstream information to CAVS on the driving behavior of HDV drivers. Drivers of unequipped cars (HDVs) receive the information on a speed limit adaptation via VSL signs above the road whereas CAVs can receive information on the upcoming speed limit more upstream. The independent variables analyzed in this research are the penetration rate of CAVs and the distance of upstream information to CAVs.

This paper is structured as follows: Section 2 sets out the methodology and the experimental design. In Section 3 describes the data processing. The experimental insights are provided in section 4. Afterwards, section 5 provides a more detailed analysis of the data. In section 6 the results are discussed, and a conclusion is provided. Section 7 presents practical recommendations for road authorities and directions for future research.

2. Method

To get insight in the driving of HDV drivers in mixed a driving simulator experiment is executed. The greatest motivation to use a driving simulator is the efficiency and effectiveness. Driving simulators are efficient because they are relatively low in cost and easy to implement compared to real life testing. Furthermore, the ability to control the experiments in terms of participants, scenarios, repeatable situations, and scenes in a driving simulator is very high. Besides, a driving simulator is effective because scenarios that cannot be tested in real traffic situations due to safety issues, not yet implemented technical solutions or rare events can be researched.

In this case, researching mixed traffic in combination with VSL can only be done in a driving simulator, while the communication between the two systems is not yet present on the current motorways.

A. Driving simulator setup

The driving simulator software used for this research is the SCANeR (v1.9) by AV Simulation. The simulator is built up from a fixed-base seating with three 4K high resolution screens providing participants a 180-degrees vision, in combination with a Fanatec steering wheel and pedals. The setup of the driving simulator is shown in Figure 1.

Figure 1. Driving simulator setup

B. Road design

Experimental design choices are established for the road environment, driving behavior of both vehicle types and the scenario design.

The road environment presented to the participants is a three-lane motorway segment installed with an VSL system based on Dutch guidelines and regulations. The VSL system has the goal to warn upstream traffic on congestion and on lower speeds downstream and to prevent crashes on traffic jam tails, the so-called Congestion Warning System. The Congestion Warning System is the most common application of a VSL system in the Netherlands [16].

A decreasing speed limit strategy from 100kmph to 70kmph and finally to 50kmph is applied. At the first Variable Message Sign (VMS) a text message is added to communicate the reason for the speed limit reduction to increase the credibility of the VSL system. The reason of the speed reduction is congestion downstream. The road section used is visualized in Figure 2. The road is divided over smaller section for analysis of the driving behavior. All sections have a length of 600m.

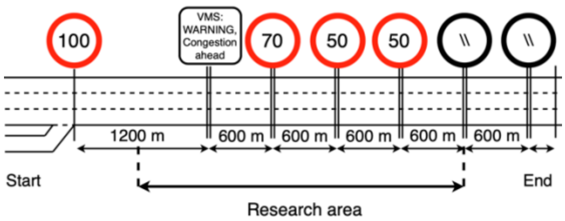


Figure 2. Road design with speed reduction strategy

The **warm-up** section starts at 600m before the warning sign and ends at the warning sign. The **approach** section goes from the warning sign to the 70 sign. The **70** section starts at the 70 sign and ends at the first 50 sign. The **50_1** is the first section where a speed limit of 50kmph is applicable and the **50_2** section the second.

C. Driving behavior design

The CAV is defined as a vehicle equipped with Cooperative Adaptive Cruise Control (CACC). This means that for the CAV only the longitudinal behavior is controlled by the automation system. The HDVs are vehicles without any in-vehicle warning or assistance systems. Therefore, the two vehicle types differ in terms of driving behavior.

CAVs are programmed to keep larger THWs (Triangular distributed, min: 1.0, max: 2.2, mode: 1.6) and keep a constant speed. The THW is based on preferred ACC settings [17]. Moreover, CAVs are assumed have a speed compliance of 100% and a preferred speed of exactly the speed limit.

HDV drivers keep on average shorter THWs compared to CAV. In this research a truncated normal distribution is used (min: 0.6, max: 2.1, mode: 1.5) [18]. The speed behavior of HDV drivers is heterogeneous and part of HDV drivers tend to speed. To model a heterogenous preferred speed for HDV drivers, a normal distribution is used with a standard deviation of 13.7% relative to the speed limit. Boundaries of +20% and -20% are used to prevent vehicles from driving either extremely fast or slow. The speeding distribution are based on Dutch motorway speed statistics of Rijkswaterstaat [19].

The lateral behavior is similar in both vehicles because the human drivers are responsible for this task in both HDVs and CAVs. The standard lane changing model of AV simulation is expanded with additional rules to get a realistic lane distribution. 70% of traffic is restricted from lane changing which get updated every 15s. Besides, triggers are placed on the road every 250 meters, to trigger 10% of vehicles to change lanes from the right lane to the middle and from the middle lane to the left lane. As a result, a normal amount of lane changes are observed and a balanced distribution of vehicles over the lanes is accomplished.

D. Scenario design

The independent variables are the penetration rate of CAVs and the distance of upstream information to CAVs from the VSL. For the penetration rate 10% and 40% of penetration rate are chosen based on future penetration rate predictions [1] and a base scenario without CAVs is added. The traffic density was fixed for all the scenarios.

The distance levels for upstream information are 300m, 600m and 900. 300m is set as the baseline as this is the first distance at which human drivers change their speed regarding a VSL [20]. 600m is chosen based on current spacing guidelines for VSLs. 900m is added as a case with an extreme distance for upstream information.

Only levels 10% and 40% of penetration rate are combined with upstream information because if no CAVs are present no upstream information can be provided. This results in a total of 7 scenarios, see Table 1. Each scenario is driven twice by the participants which adds up to a total of 14 drives. The drives are separated over two sessions with a small break in-between the sessions. Each scenario is presented once in the first session and once in second session in a randomized order in both sessions.

Table 1. Scenario design

Scenario	Pen. rate (%)	Distance[1] (m)
1	0	-
2	10	300
3	40	300
4	10	600
5	10	900
6	40	600
7	40	900

[1] The reference point for distance of upstream information is the sign at which the new speed is shown.

E. Driving behavior indicators

To analyze changes in driving behavior, driving behavior indicators need to be defined. When possible, previous literature or reports are used to define the indicators. The report of the Society of Automotive Engineers [21] is used as a leading document. The first three indicators are related to the speed adaptation behavior.

Mean speed. The mean speed is the average speed of the subject vehicle on a specific road stretch.

Section entry speed. The section entry speed is the speed of participants at the location where they pass the VSL sign.

Speed compliance. In this research speed compliance is described by the time spend below the speed limit. Less time above the speed limit equals a higher speed compliance. Because the road sections have different speed limits a relative threshold to for speeding is determined. The threshold for speeding is 110% of the posted speed limit.

Time headway. The THW is related to the car-following behavior. The THW is defined as "the time between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper)" [13, p. 9]. THWs above 6s are not taken into account because this is considered as free-flowing traffic.

Number of lane changes. A lane change is a lateral movement from one lane to the other while continuing in the same direction.

The speed and THW indicators are selected to be visualized relative to the distance because for these indicators it is most interesting to see potential differences at various distances along the road sections. The speed indicators mean speed, section entry speed and speed compliance can be derived from the speed profiles.

F. Analysis method

To test the effect of the penetration rate and upstream information the scenarios are compared with statistical tests. The effect of both independent variables, penetration rate and distance of upstream information, are analyzed for fixed levels of the other independent variable. This means that the effect of penetration rate is analyzed for three fixed distance levels of upstream information and the effect of upstream information is investigated for two fixed penetration rates.

All indicators are compared based on section averages except for section entry speed. For this indicator the speed is averaged at specific locations of the VSL signs. The indicators do not follow a normal distribution which means a non-parametric test needs to be used. Furthermore, it is a repeated measures design because the same group is used to test different conditions. Therefore, the Friedman test is used to compare multiple samples on significant differences. When a significant test result is obtained a post-hoc Wilcoxon signed rank test is executed to find out which of the scenarios statistically differ significantly from each other.

For both statistical tests a confidence level of 95% is applied.

G. Survey design

Next to the data collected from the driving simulator participants are asked to fill in a post-experiment survey. The survey consists out of two questionnaires and is used to check the validity of the driving simulator.

The first questionnaire is an existing simulator sickness questionnaire adopted from Kennedy, Lane, Berbaum & Lilienthal [23]. The questionnaires tests if participants have experienced any simulator sickness symptoms during the driving simulator experiment. The questionnaire consists out of 16 questions regarding different symptoms of physical discomfort measured on a 4-point Likert scale.

The second questionnaire relates to the subjective presence of participants in the virtual environment. An already established questionnaire by Witmer & Singer [24] is used. 32 questions with on a 7-point Likert scale are established to measure the presence.

3. Data processing

The simulator saves information on all vehicles in the scenarios at a frequency of 20Hz. To reduce the size of the extracted files the frequency is reduced to 4Hz. A frequency of 4Hz provides enough detail for the above-mentioned indicators to examine the driving behavior.

To obtain the profiles the road is divided over blocks of 25m. For each run the observations are averaged per distance block. A line can be drawn by putting all the block values behind each other. This results in an individual profile for the indicators. The individual profiles are aggregated for each scenario for all participants, and both runs to get the average behavior per scenario.

All participants drove each scenario twice. To investigate whether these runs must be treated as independent samples or not, the two runs are compared for the indicators on statistically significant differences. A Wilcoxon-signed rank test was applied while none of the run samples were normally distributed.

Table 2. Wilcoxon singed rank test result for comparing run 1 and run 2

	Run 1		Run 2		
Indicator	Mean	Std.	Mean	Std.	P-value
M. speed	66.75	4.8	67.38	4.9	0.10
Speeding	13.10	13.9	15.99	16.2	0.15
M. THW	2.79	0.7	2.66	0.7	0.09
Num LC	2.59	1.8	2.74	1.9	0.16

None of the indicators presented above shows a significant difference (<0.05) between the two samples. Therefore, both runs can be treated similar. This results in a total of 72 drives per scenario.

4. Experimental insights

In this section the participant insights and the survey results on the driving simulator validity are presented. Afterwards, the speed and THW profiles are visualized and discussed for the research area defined in Figure 2.

A. Participants and simulator insights

A total of 36 participants (27 male, 9 female) participated in the experiment ranging from 19 to 74 years old, see Figure 3. All participants had a valid driving license, and the driving experiences ranges from 1 to 50 years.

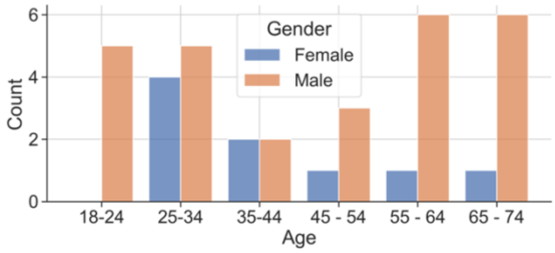


Figure 3. Age and gender distribution

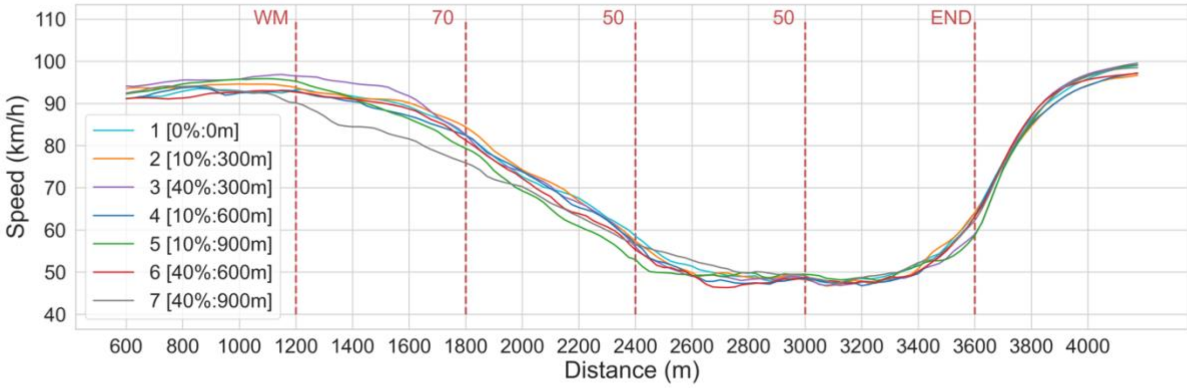


Figure 4. Speed profile per scenario

All participants scored very low on the simulator sickness score. The highest observed sickness score is 74.8 where the maximum score is 236. The average score is 24.8 (std. 19.8), which means that the simulator was very safe in terms of physical discomfort.

Most participants experienced an average presence in the virtual environment (mean: 133.5, std: 14.1). None of the participants experienced a very low presence (min: 106.0).

Based on both the presence and simulator sickness scores the data from all participants can be used for further data analysis.

B. Driving behavior insights

The speed profile is visualized in Figure 4. From a visual inspection it can be noticed that sections approach, 70 and 50_1 show most interesting differences between the scenarios in terms of speed. Scenario 7, where a high penetration rate (40%) is combined with a large distance of upstream information (900m), stands out in terms of speed compared to the other scenarios.

For the THW profile it is hard to observe consistent differences between the scenarios and sections. However, from the warning message to the end sign a slight negative trend can be observed in Figure 5. The negative trend can be explained by the lower speeds in the downstream sections.

5. Experimental results

The experiment results are divided over the effect of penetration rate and the effect of upstream information. For both penetration rate and upstream information no significant differences are found for the indicators THW and number of lane changes between the scenarios with the Friedman test, see Table 3.

This means that HDV drivers do not change their lateral driving behavior with increasing levels of penetration rate and increasing distance of upstream information provision to CAVs. Furthermore, the THW behavior of HDV drivers is not dependent on the presence of CAVs provided with upstream information.

Table 3. Friedman test result (P-value) for all scenarios per indicator and road section

Indicator	AP	70	50_1	50_2
M. speed	**0.000**	**0.000**	**0.036**	0.586
Entry speed	**0.003**	**0.000**	**0.005**	0.408
Speeding	0.095	**0.001**	**0.007**	0.647
THW	0.821	0.391	0.523	0.448
N. LC	0.987	0.410	0.333	0.850

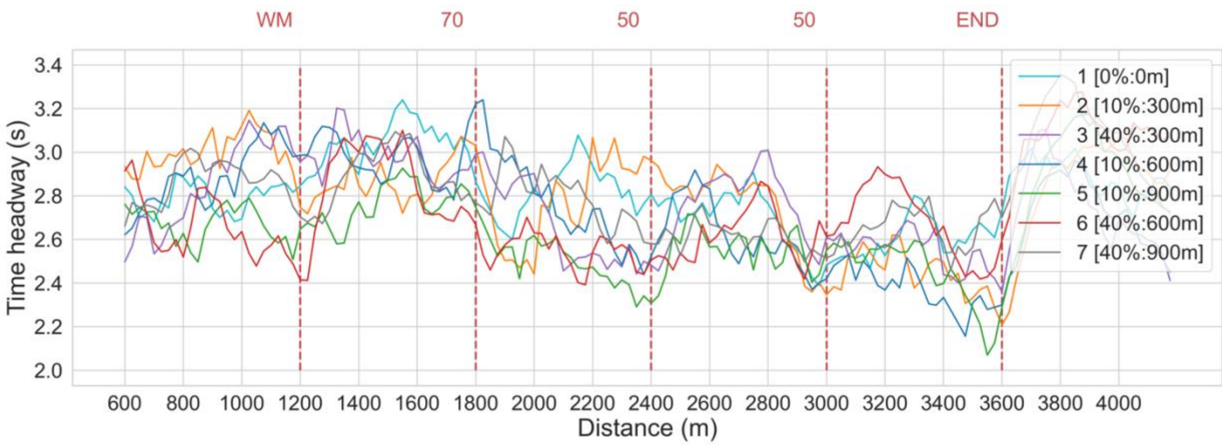


Figure 5. THW profile per scenario

For the indicators mean speed, section entry speed and speed compliance the Friedman test did result in statistically significant differences for several road sections (see table 3). For that reason, a post-hoc analysis is executed to investigate the effect in more detail for those specific indicator and section combinations.

The effects are discussed in the following sections, in combination with the Wilcoxon signed rank test statistic in brackets [Z-value, P-value].

A. Effect of penetration rate

The effect of penetration rate of CAVs is analyzed for fixed levels of upstream information. When upstream information is provided at either 300 or 600 meter no significant effect of penetration is rate is found for all three speed indicators.

This means that just adding AVs to the total traffic does not necessarily result into traffic slowing more upstream at VSL signs.

In case the speed limit is shared with CAVs at 900 meters the effect of penetration rate becomes significant. A penetration of 10% of CAVs decreases the mean speed in the 70 section by 7% from 69.6 to 64.7 kmph [-3.608, <0.001]. Besides, the section entry speed of the 70 section decreases by 3.2 kmph [-2.593, 0.010] and 5.6 kmph [-3.541, <0.001] for the 50_1 section. The speed compliance increases for sections 70 and 50_1 by 3.2s [-2.846, 0.004] and 2s [-2.224, 0.026].

For a penetration of 40% a significant decrease in mean speed is observed in the approach section by 8% from 89.7 to 82.6 kmph [-4.444, <0.001], and the 70 section by 6%, from 69.6 to 65.8 kmph [-2.609, 0.009]. Furthermore, the entry speed of the 70 section is lowered with 6.6 kmph [-2.458, 0.014] and the speed compliance increases for the 70 section with 3.1s [-2.128, 0.033].

The biggest difference with varying levels of penetration rate is the location at which HDV drivers start to adapt their speed. For a penetration rate of 10% drivers start to decelerate more upstream compared to 0%. When the penetration rate is increased to 40%, HDV drivers start to decelerate even more upstream compared to 0% and 40%.

B. Effect of upstream information

The effect of upstream information to CAVs on the speed adaptation behavior of HDV drivers is analyzed for two fixed levels of penetration rate, 10% and 40%.

At a penetration rate of 10% the speed indicators only show significant differences by upstream information if this is provided at 900 meters. This means that providing information to CAVs at 600 meters with a low penetration rate (10%) has no effect on the driving behavior of HDV drivers.

If the information is provided at 900 meters upstream the mean speed is lowered by 8% from 70.08 to 64.76 kmph [-3.973, <0.001] in the 70 section. Furthermore, the section entry speed decreases for the 70 section by 5.0 kmph [-3.670, <0.001] and for the 50_1 section by 4.4 kmph [-2.666, 0.008]. Besides, the speed compliance increases in the 70 section by 3.9s [-3.078, 0.002].

In case the penetration rate of CAVs increases to 40%, significant results are found for both 600 and 900 meters of upstream information.

With 600 meter of upstream information the mean speed is decreased in the approach section by 3% from 92.0 to 88.95 kmph [-2.576, 0.007]. The section entry speed is lowered for the approach section by 3.8 kmph [-2.682, 0.007] and no effect is found for speed compliance.

With 900 meters of upstream information for more road sections significant differences are found. The mean speed is decreased in the approach and 70 section. In the approach section a decrease of 10% is realized from 92.0 to 82.61 kmph [-5.511, <0.001]. In the 70 section the mean speed is lowered by 5%, from 69.2 to 65.8 kmph [-2.626, 0.009].

The section entry speed in the approach section is lowered with 6.5 kmph [-4.080, <0.001] and in the 70 section with 6.6 kmph [-3.782, <0.001]. The speed compliance increases slightly for the 70 section with 2.1s [-2.065, 0.039] but decreases in the 50_1 section with 5.3s [-2.133, 0.033].

Differences in speed behavior of HDV drives are found for varying levels for distance of upstream information to CAVs.

At 600 meters only a few road sections show significant differences for the speed indicators. When the distance is increased to 900 meters more road sections show a difference in speed behavior.

This means that the effect of upstream information becomes more noticeable when provided at a large distance.

6. Discussion and conclusion

Compared to previous literature on behavioral adaptation the result that no change in driving behavior is observed when CAVs are introduced without upstream information is surprising [9], [10], [14]. One explanation could be that although differences in driving behavior are present between HDVs and CAVs, the differences are not distinct enough to induce a change in driving behavior. Another explanation could be that CAVs where not recognizable in this research, which means that participants did not know which and how many of the surrounding vehicles were a CAV or HDV.

Only when the introduction of CAVs is combined with upstream information at 900 meters significant differences are found in speed adaptation behavior for the different levels of penetration rates.

This can be a logical result because when providing more upstream information, the change in driving behavior of CAVs becomes more apparent.

It can be concluded that different levels of penetration rate of CAVs on itself does not induce a change in driving behavior, whereas it does in combination with a large distance of upstream information.

Providing information at a low penetration rate of CAVs (10%) only makes sense if the information is provided at a large distance upstream (900 meters). In case the penetration rate increases to 40% more significant results are found. The effect of 900 meters upstream information is observed in more sections. For 600 meters upstream information driving behavior of HDV drivers changes as well but not to the same extent compared to 900m.

The findings on speed adaptation behavior can be explained by previous studies which found that human drivers tend to slow down earlier when following a slower leader [25]. When part of the traffic is provided with upstream information more slower leaders are introduced in the traffic flow.

It may be concluded that providing upstream information on the speed limit has the most effect if it is provided at a large distance upstream of the actual VSL. Furthermore, the benefits of upstream information are expanded when more CAVs are present on the road.

In this research it is found that the cooperation between a VSL system and CAVs can contribute to slow down the traffic flow when approaching and a reduction of the speed limit. The speed limit can be communicated to CAVs without inducing aggressive behavior of HDV drivers in terms of THW, number of lane changes and duration of lane changes.

7. Recommendations

First practical recommendations for road authorities are provided. Afterwards, recommendations for future research are discussed.

A. Practical recommendations

If the cooperation between VSL signs and CAVs is to be implemented a large distance of upstream information should be considered. Moreover, a standardized communication technology should be chosen and made mandatory for new developed vehicles to increase the penetration rate of CAVs.

Moreover, communicating the speed limit to part of the traffic could be expanded to other use cases on the road. Potential examples are roadblocks or road construction sites with reduced speed limits and coordination of speed limits to prevent or suppress shock waves on motorways.

A more in-depth study is needed to find the most efficient distance of upstream information regarding the road environment in terms of number of lanes, speed limit and speed reduction.

For road authorities it is important to investigate how to implement a system where part of the traffic is used to slow down surrounding. The incentive for CAV drivers is not obvious because they are the ones that are impacted most by reduced speed limits. Potential incentives could be road tax reductions or a discount on car insurance.

B. Scientific recommendations

In this research a fixed level of traffic density was chosen to limit the complexity. However, it is expected that the traffic density has an influence on the adaptation of driving behavior because the traffic density determines the level of freedom in driving behavior choices in terms of preferred speed and lane choice. It is interesting to investigate whether the same results are found when the traffic density either increases or decreases. Besides, more research is needed regarding different compositions of vehicle types on the road. This research excluded vans and trucks.

Next to this, more variability could be added to the speed reductions participants encounter to overcome potential learning effects during the experiment.

Furthermore, it would be interesting to investigate the effect of upstream information in combination with other information systems. For example, HDV drivers could be provided with in-car information devices to inform them more upstream as well. This would mean that such information systems could also work when no next to the road infrastructure to share VSL is present.

The data could be analyzed on a more disaggregate level to get a better understanding in the individual behavior of HDV drivers regarding the changed traffic environment.

Research making use of microscopic models should update the driving behavior models of human drivers based on these findings when modeling mixed traffic in combination with VSL on motorways. Furthermore, these models can then be used to determine the best distance of upstream information for different levels of penetration rate of CAVs.

References

[1] D. Milakis, M. Snelder, B. van Arem, B. van Wee, and G. H. de A. Correia, ‘Development and transport implications of automated vehicles in the Netherlands: scenarios for 2030 and 2050’, *EJTIR*, vol. 17, no. 1, Jan. 2017, doi: 10.18757/ejtir.2017.17.1.3180.

[2] B. Khondaker and L. Kattan, ‘Variable speed limit: A microscopic analysis in a connected vehicle environment’, *Transportation Research Part C: Emerging Technologies*, vol. 58, pp. 146–159, Sep. 2015, doi: 10.1016/j.trc.2015.07.014.

[3] Y. Li, H. Wang, W. Wang, S. Liu, and Y. Xiang,

‘Reducing the risk of rear-end collisions with infrastructure-to-vehicle (I2V) integration of variable speed limit control and adaptive cruise control system’, *Traffic Injury Prevention*, vol. 17, no. 6, pp. 597–603, Aug. 2016, doi: 10.1080/15389588.2015.1121384.

[4] X. Qi, T. Sun, W. Ma, L. Wang, and C. Yu, ‘Evaluation of a variable speed limit system using a hierarchical framework under a connected vehicles environment: a case study of a field test in Seattle’, *IET Intelligent Transport Systems*, vol. 14, no. 9, pp. 1125–1131, 2020, doi: https://doi.org/10.1049/iet-its.2019.0858.

[5] J. R. D. Frejo, I. Papamichail, M. Papageorgiou, and B. De Schutter, ‘Macroscopic modeling of variable speed limits on freeways’, *Transportation Research Part C: Emerging Technologies*, vol. 100, pp. 15–33, Mar. 2019, doi: 10.1016/j.trc.2019.01.001.

[6] N. van Nes, S. Brandenburg, and D. Twisk, ‘Improving homogeneity by dynamic speed limit systems’, *Accident Analysis & Prevention*, vol. 42, no. 3, pp. 944–952, May 2010, doi: 10.1016/j.aap.2009.05.002.

[7] T. Pan, R. Guo, W. H. K. Lam, R. Zhong, W. Wang, and B. He, ‘Integrated optimal control strategies for freeway traffic mixed with connected automated vehicles: A model-based reinforcement learning approach’, *Transportation Research Part C: Emerging Technologies*, vol. 123, no. 102987, Feb. 2021, doi: 10.1016/j.trc.2021.102987.

[8] A. Papadoulis, M. Quddus, and M. Imprialou, ‘Evaluating the safety impact of connected and autonomous vehicles on motorways’, *Accident Analysis & Prevention*, vol. 124, pp. 12–22, Mar. 2019, doi: 10.1016/j.aap.2018.12.019.

[9] M. Gouy, K. Wiedemann, A. Stevens, G. Brunett, and N. Reed, ‘Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers’ longitudinal control?’, *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 27, pp. 264–273, Nov. 2014, doi: 10.1016/j.trf.2014.03.003.

[10] Y. Rahmati, M. Khajeh Hosseini, A. Talebpour, B. Swain, and C. Nelson, ‘Influence of Autonomous Vehicles on Car-Following Behavior of Human Drivers’, *Transportation Research Record*, vol. 2673, no. 12, pp. 367–379, Dec. 2019, doi: 10.1177/0361198119862628.

[11] M. Schoenmakers, D. Yang, and H. Farah, ‘Car-following behavioural adaptation when driving next to automated vehicles on a dedicated lane on motorways: A driving simulator study in the Netherlands’, *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 78, pp. 119–129, Apr. 2021, doi: 10.1016/j.trf.2021.01.010.

[12] I. Mahdinia, A. Mohammadnazar, R. Arvin, and A. J. Khattak, ‘Integration of automated vehicles in mixed traffic: Evaluating changes in performance of following human-driven vehicles’, *Accident Analysis and Prevention*, vol. 152, 2021, doi: 10.1016/j.aap.2021.106006.

[13] S. Y. Lee, C. Oh, and S. Hong, ‘Exploring lane change safety issues for manually driven vehicles in vehicle platooning environments’, *IET Intelligent Transport Systems*, vol. 12, no. 9, pp. 1142–1147, 2018, doi: 10.1049/iet-its.2018.5167.

[14] S. I. Lee and C. Oh, ‘Lane Change Behavior of Manual Vehicles in Automated Vehicle Platooning Environments’, *Journal of Korean Society of Transportation*, vol. 35, no. 4, pp. 332–347, 2017, doi: 10.7470/jkst.2017.35.4.332.

[15] J. H. Hogema, ‘Modeling Motorway Driving Behavior’, *Transportation Research Record*, vol. 1689, no. 1, pp. 25–32, Jan. 1999, doi: 10.3141/1689-04.

[16] F. Beemster, I. Wilmink, and H. Taale, ‘Vervanging wegkantsystemen door in-carsystemen: Een quick scan analyse’, TrafficQuest, Delft, 2017. [Online]. Available: http://resolver.tudelft.nl/uuid:a55fef40-51f7-4aa1-8303-fc158abce7cf

[17] T. P. Alkim, G. Bootsma, and S. P. Hoogendoorn, ‘Field Operational Test “The Assisted Driver”’, in *2007 IEEE Intelligent Vehicles Symposium*, Jun. 2007, pp. 1198–1203. doi: 10.1109/IVS.2007.4290281.

[18] M. Brackstone, B. Waterson, and M. McDonald, ‘Determinants of following headway in congested traffic’, *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 12, no. 2, pp. 131–142, Mar. 2009, doi: 10.1016/j.trf.2008.09.003.

[19] Rijkswaterstaat Water, Verkeer en Leefomgeving, ‘Veilig over Rijkswegen 2019 : monitoringsrapport verkeersveiligheid van rijkswegen : deel A: landelijk beeld’, Rijkswaterstaat, PUC_640042_31, Mar. 2020. Accessed: Sep. 03, 2021. [Online]. Available: https://puc.overheid.nl/doc/PUC_640042_31

[20] M. Matowicki and O. Pribyl, ‘A driving simulation study on drivers speed compliance with respect to variable message signs’, *Journal of Intelligent Transportation Systems*, pp. 1–11, May 2021, doi: 10.1080/15472450.2021.1926247.

[21] SAE, ‘Operational Definitions of Driving Performance Measures and Statistics’, SAE International, Jun. 2015. [Online]. Available: https://www.sae.org/standards/content/j2944_201506/

[22] TRB, *Highway capacity manual 2010, Volumes 1-4*. Washington, DC: Transportation Research Board, 2010.

[23] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, ‘Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness’, *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, Jul. 1993, doi: 10.1207/s15327108ijap0303_3.

[24] B. G. Witmer and M. J. Singer, ‘Measuring Presence in Virtual Environments: A Presence Questionnaire’, *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, pp. 225–240, Jun. 1998, doi: 10.1162/105474698565686.

[25] S. F. Varotto, R. Jansen, F. Bijleveld, and N. van Nes, ‘Driver speed compliance following automatic incident detection: Insights from a naturalistic driving study’, *Accident Analysis & Prevention*, vol. 150, p. 105939, Feb. 2021, doi: 10.1016/j.aap.2020.105939.

B. Questionnaires

B.1 Pre-experiment

Demographic questionnaire:

1. What is your name?
2. What is your e-mail?
3. What is your gender? (male/female/intersex)
4. What is your date of birth? (date)
5. What is your level of education? (WO/HBO/MBO/High-school/none of the above)
6. How much years of driving experience do you have? (number)
7. How much kilometers do you drive on average per year? (0-5k, 5k-1k, 1k- 15k, 15k+)
8. How many times per week on average do you use the motorway? (0-2, 2-5, 5+)
9. Do you own a car that is equipped with ACC? (yes/no)

Driving style questionnaire (PADI)

Could you please indicate in the provided scale how often you engage in each of the stated driving behaviors? A 6-point Likert scale (never, almost never, sometimes, fairly often, very often, always). Questionnaire adopted from (Harris et al., 2014). Items 1-17 (17 items) belong to pro-social driving, items 18-29 (12 items) relate to aggressive driving.

1. Drive with extra care around pedestrians
2. Pay special attention when approaching intersections
3. Drive with extra care around bicyclists
4. Pay special attention when making turns
5. Pay attention to traffic and my surroundings while driving
6. Break slowly enough to alert drivers behind me
7. Decrease speed to accommodate poor road conditions
8. Use mirrors and check blind spots when changing lanes
9. Drive more cautiously to accommodate people or vehicles on the side of the road (e.g., slow down, move over)
10. Maintain a safe distance when following other vehicles
11. Slow down in a construction zone
12. Come to a complete stop at a stop sign
13. Decrease speed to accommodate poor weather conditions
14. Yield when the right of way belongs to other drivers
15. Obey traffic signs
16. Obey posted speed limits in a school zone
17. Use turn signals (blinkers) to notify other drivers of my intention to turn
18. Weave in and out of lanes to overtake traffic
19. Speed up when another vehicle tries to overtake me
20. Follow the vehicle in front of me closely to prevent another vehicle from merging in front of me
21. Pass in front of a vehicle at less than a car length
22. Merge into traffic even when another driver tries to close the gap between vehicles
23. Accelerate into an intersection when the traffic light is changing from yellow to red
24. Drive 15 miles per hour (25 kmph)faster than the posted speed limit
25. Flash my high beams at a slower vehicle so that it will get out of my way
26. Make rude gestures at other drivers when they do something I do not like
27. Honk when another driver does something inappropriate
28. Pass other vehicles using the right lane
29. Follow a slower vehicle at less than a car length

Experience questionnaire:
Questionnaire is used for both ACC and VSL. Questionnaire is adopted from (Van Der Laan et al., 1997). Experience questionnaire can be subdivided over two sub-scales. The first sub-scale relates to the usefulness and is represented by items 1,3,5,7,9. The second sub-scale relates to the satisfaction and is represented by items 2,4,6,8.

Could you please indicate below what your opinion is about ACC/VSL? A 5-point Likert scale is used.

1. Useful – useless
2. Pleasant – unpleasant
3. Bad – good
4. Nice – annoying
5. Effective – Superfluous
6. Irritating – likeable
7. Assisting – worthless
8. Undesirable – desirable
9. Raising alertness – sleep-inducing

B.2 During-experiment

Experience during scenario:

Open question

1. How did you experience the scenario?

On a 7 point Likert scale is used from *low* to *high*.

1. How much mental activity was required (thinking, deciding, calculating, looking, searching, etc.) to accomplish your level of performance?
2. How safe did you feel related to the surrounding traffic? (safe to unsafe)
3. How relaxed did you feel during the experiment? (relaxed to frustrated)
4. Were you able to drive “freely”? / Did you feel blocked or held up by surrounding traffic?
5. To what extend where you able to drive your preferred speed?

B.3 After-experiment

Presence in virtual environment: Questionnaire is used to measure the subjective feeling of participants being present in the experiment en involved with the scenario. The questionnaire is adopted from (Witmer & Singer, 1998).

A 7 point Likert scale is used from *none at all* to *fully*

1. How much were you able to control events?
2. How responsive was the environment to actions that you initiated (or performed)?
3. How natural did your interactions with the environment seem?
4. How completely were all of your senses engaged?
5. How much did the visual aspects of the environment involve you?
6. How much did the auditory aspects of the environment involve you?
7. How natural was the mechanism which controlled movement through the environment?
8. How aware were you of events occurring in the real world around you?
9. How aware were you of your display and control devices?
10. How compelling was your sense of objects moving through space?
11. How inconsistent or disconnected was the information coming from your various senses?

12. How much did your experiences in the virtual environment seem consistent with your real-world experiences?
13. Were you able to anticipate what would happen next in response to the actions that you performed?
14. How completely were you able to actively survey or search the environment using vision?
15. How well could you identify sounds?
16. How well could you localize sounds?
17. How well could you actively survey or search the virtual environment using touch?
18. How compelling was your sense of moving around inside the virtual environment?
19. How closely were you able to examine objects?
20. How well could you examine objects from multiple viewpoints?
21. How well could you move or manipulate objects in the virtual environment?
22. To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?
23. How involved were you in the virtual environment experience?
24. How distracting was the control mechanism?
25. How much delay did you experience between your actions and expected outcomes?
26. How quickly did you adjust to the virtual environment experience?
27. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
28. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
29. How much did the control devices interfere with the performance of assigned tasks or with other activities?
30. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
31. Did you learn new techniques that enabled you to improve your performance?
32. Were you involved in the experimental task to the extent that you lost track of time?

Simulator sickness questionnaire: A simulator sickness questionnaire is used from (Kennedy et al., 1993). Participants rate their physical experience on a 4 point Likert scale (0-3)

1. General discomfort
2. Fatigue
3. Headache
4. Eyestrain
5. Difficulty focusing
6. Increased salivation
7. Sweating
8. Nausea
9. Difficulty concentrating
10. Fullness of head
11. Blurred vision
12. Dizzy (eyes open)
13. Dizzy (eyes closed)
14. Vertigo
15. Stomach awareness
16. Burping

C. Inform & consent

C.1 Information Sheet for Participants

Please read this information sheet carefully before signing the consent form. If you decide to participate, your signature will be required. If you desire a copy of this information sheet and consent form, you may request one.

Research title

Driving behavior in mixed traffic in combination with variable speed limit.

Researchers

Jitse Wiersma – MSc student, TU Delft
Email: J.S.Wiersma@student.tudelft.nl
Phone: +31 681230144

Dr. ir. Haneen Farah
Email: h.farah@tudelft.nl

Ir. Nagarjun Reddy
Email: N.Reddy@tudelft.nl

Erna Schol
Email: erna.schol@rws.nl

Purpose of study

The purpose of this research study is to understand behavioral adaptation of traditional human drivers in mixed traffic in combination with variable speed limit. The behavior is studied to improve traffic safety and efficiency.

Experimental procedure and instructions

In this research study, you will be asked to drive in a driving simulator on a designated route that contains routine driving situations along with other traffic.

You will be asked to fill in an online questionnaire during and after the experiment. This experiment will take about 70 minutes of your time. This time also includes briefing to explain the experiment and breaks between different scenarios. Further instructions will be provided during the experiment.

Before the experiment

On the day of the experiment, you will be briefed shortly about the experiment where other instructions will be made clear to you.

During the experiment

First, you will be allowed to drive freely in the driving simulator to get familiarized and comfortable with the equipment and environment. At the start of every scenario, you will receive an indication from the researcher to start driving (in the simulator). You are expected to perform normal driving behavior on a motorway. While driving, you are free to make your driving decisions. Your only objective during the driving would be drive like you would behave in a real-life context.

Once you reach the destination, which is one scenario, you will be asked questions about your experience while driving. Similar task will be provided to you in all the driving scenarios, excluding the familiarisation drive.

After the experiment

After all scenarios of driving and a small break, you will be asked to fill a 2-minute-long online questionnaire related to your driving experiences.

Risks and safety

We believe that there are no major risks associated with this research study. However, some of the participants might experience minor nausea while driving in the simulator. To minimise nausea, the driving scenarios are designed for shorter duration. If you experience discomfort, you can withdraw from the experiment at any instance.

Strict approved measures are followed to minimise the risk of spreading coronavirus and ensure safety of participants and researcher. All the study equipment will be sanitized after every participant use. If you have symptoms, we request you not to attend the experiment for the safety of you and others.

Data storage and confidentiality

We will safely store data in a secured research repository called Project Storage at TU Delft. The data is regarded as confidential, and it will not be shared with external users beyond study group researchers. A month after the end of experiment, the data from both phases is anonymized and aggregated. During this process, personal data such as name, age group, profession, driving experience, gender, social preferences, and email addresses will be deleted from the database. If you need information on your data, please contact the researcher within a month after the experiment. After this period, we cannot trace back and provide you the data as the processed data will not have your personal information. Observations will be generated from the processed data and the observations might be published in the academic proceedings. The processed data will be shared on 4TU.Research for future research purposes.

Participant rights

Your participation in this experiment is voluntary. So, you have the right to refuse to follow instructions of the experiment. You also have a right to ask questions about this research at any stage of the experiment. In addition, you have the right to withdraw at any stage of this research. If so, your data will not be used for analysis and it will be deleted from all the databases.

Please express your consent by filling the questionnaire below.

C.2 Consent form

Please tick the appropriate boxes [yes/no]

Taking part in the study

- I have read and understood the study information dated [DD/MM/YYYY], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.
- I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.
- I understand that taking part in the study involves driving in a driving simulator and completing questionnaires before, during and after the experiment that will include questions related to experiences during the experiment.

Risks associated with participating in the study

- I understand that the study in a driving simulator could cause minor nausea and that I can stop the experiment at any time I so desire.

Use of the information in the study

- I understand that information I provide will be used in reports, scientific publications or may be presented in conferences on traffic safety, traffic psychology, or relevant fields
- I understand that personal information collected about me that can identify me, such as my name, email address or contact details, gender, age group, profession and education level will not be shared to anyone beyond the study team.
- I agree that my answers in the survey questionnaires can be quoted in research outputs anonymously

Future use and reuse of the information by others

- I give permission that all the data collected during the experiment and questionnaires filled by me can be archived anonymously in the repository of TU Delft so it can be used for future research and learning

Distancing

- I do not participate if I have cold-like symptoms, or cough, or experience a shortness of breath, loss of smell or taste, or have a fever Travelling

Hygiene

All objects and surfaces a participant can come into contact during the experiment will be disinfected before and after the experiment.

Signatures

Name of participant:
Date:
Signature:

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Jitse Siebrand Wiersma
Date:
Signature:

In case of any questions / doubts / clarifications regarding the study or your rights as a research participant, contact:
Jitse Siebrand Wiersma
+31 681230144,
J.S.Wiersma@student.tudelft.nl

D. Pre-experiment briefing

Responsible researchers & contact information

Jitse Wiersma – MSc student, TU Delft
Email: J.S.Wiersma@student.tudelft.nl
Phone: +31 681230144

Dr. ir. Haneen Farah
Email: h.farah@tudelft.nl

Ir. Nagarjun Reddy
Email: N.Reddy@tudelft.nl

Pre-experiment briefing

Dear participant,

Thank you for taking part in the experiment. You are about to start driving in the driving simulator. This sheet briefs you on the important things you need to know before you can start. So, please take your time and read this document carefully. If anything is unclear to you, please don't hesitate to ask the researcher.

About the experiment

The goal of this study is to analyze the driving behavior of future traffic situations on motorways in combination with variable speed limits. You will drive multiple scenarios where you will encounter surrounding traffic. You are asked to drive as you would normally drive in a real-life context.

Time required

The driving simulator experiment consists out of two sessions, each consisting of 7 scenarios. Between each two consecutive scenarios you can take a short break and after the first session you can have a longer break (5-10 minutes). The total time for the driving simulator, and questionnaires during the experiment will not take more than 90 minutes.

Risks & safety

We believe that there are no major risks associated with this driving simulator study. However, it could be possible that you experience minor nausea or other unpleasant symptoms. Remember that you can withdraw at any moment if you feel the need to or ask for an additional break. Please report any discomfort to the researcher at any instance.

Experimental steps

First, you will drive a "test-drive" to get familiar with the driving simulator controls and the virtual environment. You will drive on a straight motorway section, and you can drive in any way you want. The "test-drive" will take about 4 minutes and you can request more time if needed.

Once you are familiar with the driving simulator, you will start the experiment. Imagine the following situation for the scenarios:

"You are travelling from Delft to Rotterdam/The Hague Airport to pick up a friend. You are a bit in a hurry because your friend is already waiting for you at the airport. To reach the airport you need to drive on a motorway until the exit to the airport is reached."

The distance between the starting point and the exit is around 8 kilometers. During the drive you can make your own driving decisions in terms of preferred speed, lane choice etc. However, as in normal traffic, you are being asked to follow the traffic regulations. Try to drive and behave as you would drive in real life.

After indication of the researcher, you can start driving to complete your task as described above. The scenario will stop automatically when you have reached the end of the scenario. After each scenario you will be provided with a short questionnaire on your experience regarding the last run. The researcher will prepare the next scenario and will indicate when it is ready for you to drive the next scenario.

In total you will drive 14 scenarios (2 sessions x7 scenarios) which each will take about 4 minutes.

End of the experiment

After you have finished the driving simulator experiment you will be provided with a final questionnaire to ask about your experience in the driving simulator. After this point you have successfully completed the full experiment, and you will be rewarded with a voucher of 15€.

Confidentiality

All the data collected in this experiment will be kept confidential. All the personal details about you will be anonymized to ensure that you are not personally identifiable in any document or dataset resulting out of this study. All the data collected during the experiment will be kept secured in the data archives of TU Delft. The data will only be made accessible to the researchers involved in this study. The data will only be used for scientific analysis during the researcher's research and possible future extensions of the research. The findings from this experiment may be published in scientific journals, research papers or maybe presented in conferences related to traffic safety, traffic psychology or driving behaviour. The findings from this research may be used in other studies related to traffic psychology, safety or driving behaviour.

Right to refuse & withdraw

Your participation in this study is entirely voluntary. You have the right to refuse or withdraw from this experiment at any time. By agreeing to participate in this study you do not surrender your rights and do not free the researchers, sponsors or institutions involved from legal and professional obligations.

Questions & Contact

You can contact Jitse Wiersma (see top for contact details) in case of any questions / doubts / clarifications regarding the study or your rights as a research participant.

I have read and completely understood the pre-experiment briefing in this document.

Name:

Signature:

E. Driving simulator data extraction

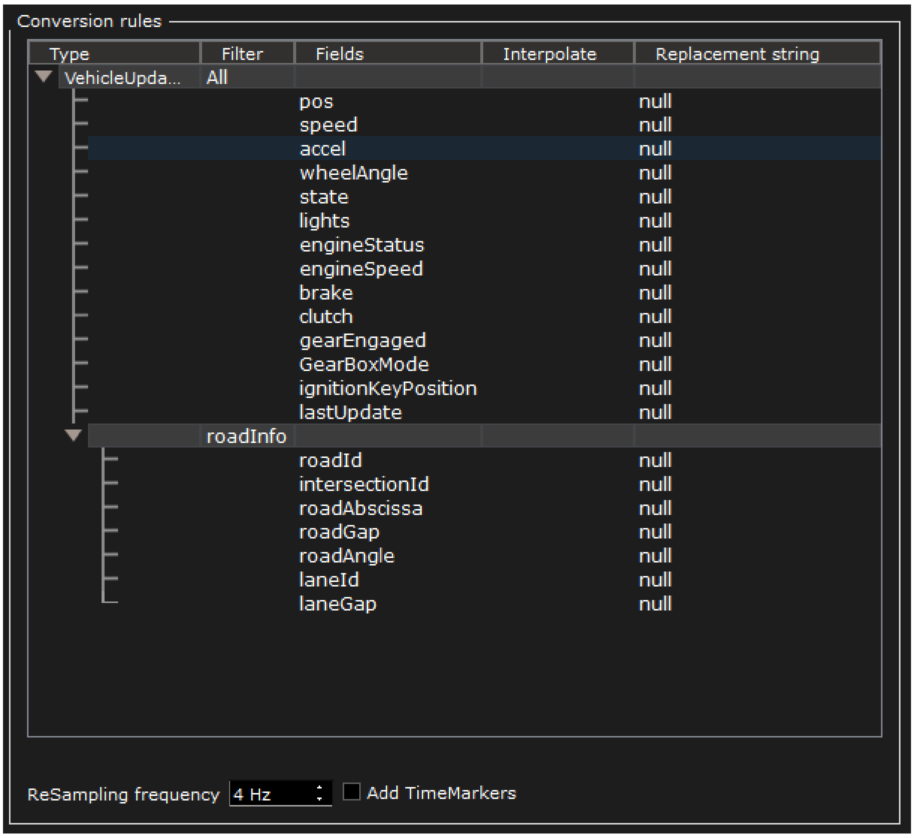
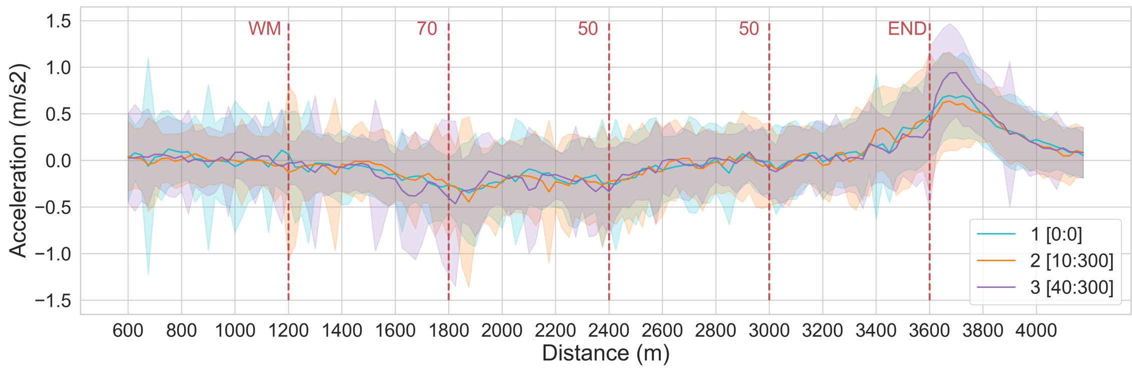
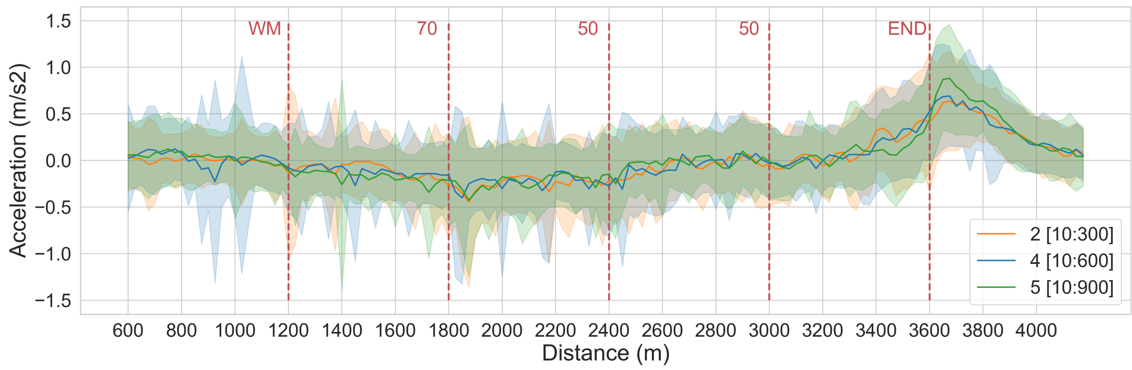


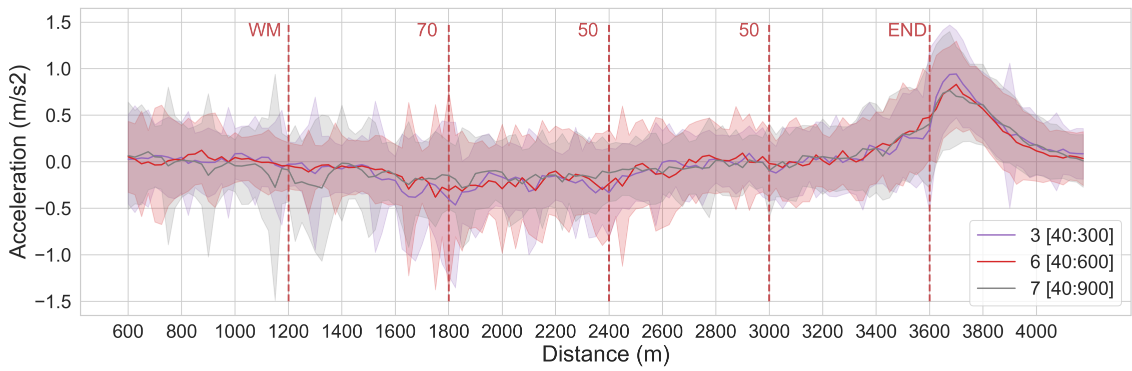
Figure E.1: Extracted variables from Scanner



(a) Base scenarios

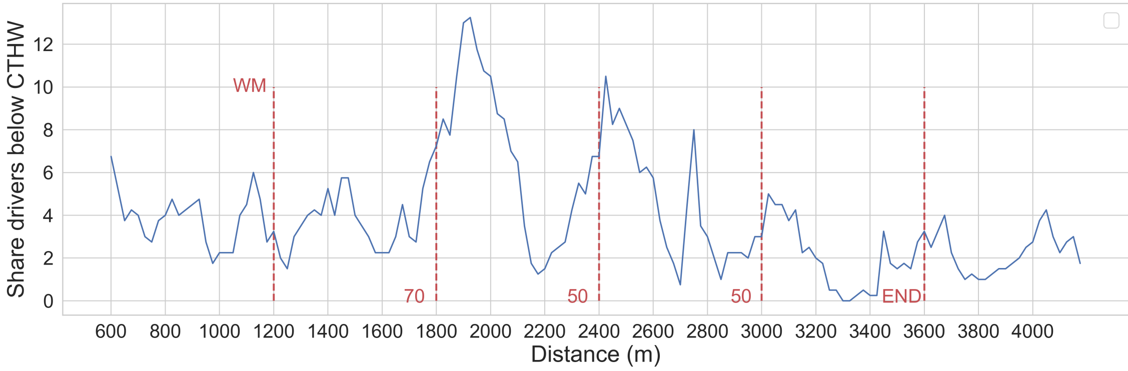


(b) 10% penetration rate

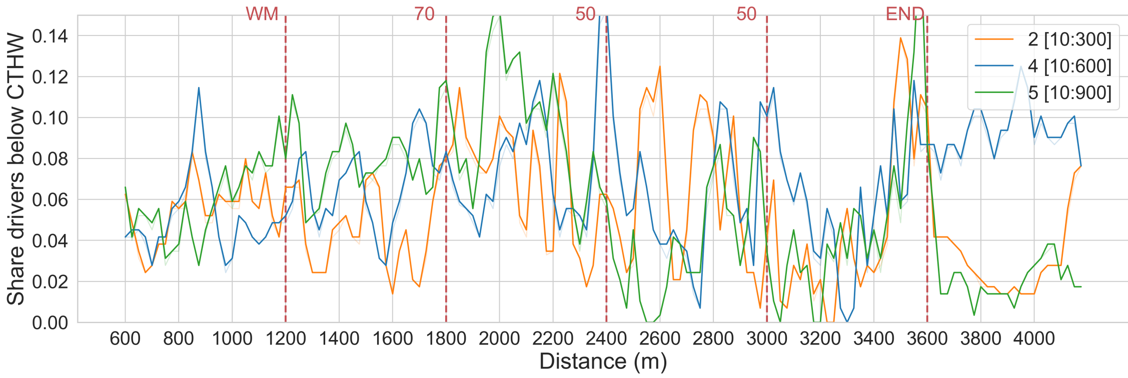


(c) 40% penetration rate

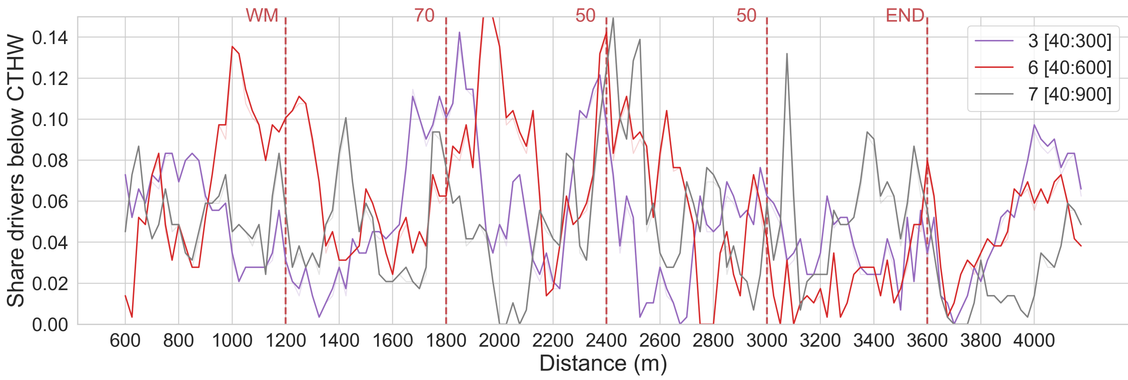
Figure F.1: Mean acceleration



(a) Base scenarios



(b) 10% penetration rate



(c) 40% penetration rate

Figure F.2: Share of drivers below a time headway of 1 second