Automated Vehicles and Infrastructure Design

An insight into the implications of a dedicated lane for Automated Vehicles on the highway in the Netherlands

Thesis Master of Science

Automated Vehicles and Infrastructure Design

An insight into the implications of a dedicated lane for Automated Vehicles on the highway in the Netherlands

M.J.(Mathijs) Schoenmakers
0805394
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Master Construction Management and Engineering
Eindhoven University of Technology
Delft University of Technology

Thesis committee

Prof. dr. ir. B. de Vries	Eindhoven University of Technology	Construction Management and Engineering
Dr. D. Yang	Eindhoven University of Technology	Construction Management and Engineering
Dr. ir. H. Farah	Delft University of Technology	Transport and Planning
Drs. T. Alkim	Rijkswaterstaat	Ministry of Infrastructure and Water Management

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Preface

Dear reader,

This thesis is the final product of my career as a student. I feel happy and grateful that I was able to graduate on a topic this close to my interests. I am glad the universities made it possible to step out of my comfort zone and conduct research in the field of mobility and traffic engineering. This thesis provides insights into the implications of a dedicated lane for Automated Vehicles. I hope this thesis can actually contribute to the long way we still have to go to improve mobility with the implementation of automated systems.

First, I would like to thank my supervisors, Dujuan, Haneen and Tom, who provided me with feedback, support and guidance during the entire process of writing this thesis. I would like to give a special thanks to both Universities. Eindhoven University of Technology, who made it this easy and convenient and possible in the first place, to collaborate for this thesis with Delft University of Technology. And Delft University of Technology, who was open to and supporting for such a collaboration. Special thanks to all the employees and students at Delft University of Technology who were so welcoming and helpful during the months I spent there, conducting my experiment. Obviously, I would also like to thank my colleagues from Rijkswaterstaat who provided me with feedback, insights, for the opportunities to learn and the fun times during the past months. Furthermore, I would also like to thank my friends and family for their continuous support over the past years.

Personally, I am very happy that I am able to complete my student years with this thesis. I enjoyed the past years at the university so much and will look back with only good memories, including writing this thesis. I will definitely miss my student years, but new adventures lie ahead.

Best,

Mathijs Schoenmakers
Eindhoven, March 2018

Summary

Road traffic will increase in the upcoming years due to urbanization. In the Netherlands, there has been an increase of 20% in mobility in the last 10 years (Rijksoverheid, 2008). It is expected that this trend will continue. Automated Vehicles (AVs), as one of the solutions, are expected to contribute to improve the traffic flow efficiency, traffic safety, and the environment. However, deployment is facing many challenges considering complex traffic situations and the urban built environment. Comparing to driving in a city environment, driving on highways is a relatively simple driving environment for AVs. The implementation of AVs on highways is expected to be the most promising first step in the near future. Nevertheless, to actually make this happen an in-depth understanding and consensus is necessary on how to adapt the highway infrastructure to future mobility. One of the concerns regarding the deployment of AVs on existing highways is the mixed traffic situation, where automated vehicles and manually driven vehicles (MVs) share the road. Different studies suggest a dedicated lane as a solution to overcome these concerns. However, evidence-based research on the implications of dedicated lanes on traffic flow efficiency and behavioral adaptation of drivers of manual vehicles is still missing. Therefore, the main research question of this study is: ***How is drivers' behavior influenced by the implementation of a dedicated lane for automated vehicles on the highway in the Netherlands and what are the implications on traffic flow efficiency?***

To answer this research question, and in order to get insights into the implications of the implementation of a dedicated lane for AVs on the behavioral adaptation of manually driven vehicles and on traffic flow efficiency two research methodologies have been combined. First a driving simulator experiment was designed. In this experiment four scenarios for a dedicated lane have been developed: the baseline scenario without a dedicated lane, a continuous access lane and two limited access lanes, one with a guardrail separation and one with a continuous white line separating the lanes. The four developed lane scenarios have been tested in a driving simulator experiment to obtain insights into the behavioral adaptation of drivers of manually driven vehicles in the proximity of a dedicated lane for automated vehicles. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean Time Headway (THW) differed statistically significantly between the four different scenarios. The results showed that drivers of manually driven vehicles drove with a significant lower THW when they drove in the proximity of a platoon on the continous access lane and on a limited acess lane with a continous line as a seperation along part of the road, than when the AVs were driving on the limited access lane with a guardrail separation. The THW the participants maintained on the limited access lane with a guardrail separation was similar to the observed baseline scenario with no platoon of AVs driving on a dedicated lane and only the leading vehilce on the road. Moreover, a linear mixed effect model was applied to predict the impact of the different scenarios on the THW of MVs. In this model, the scenario factor was found to be significant, confirming the repeated measures ANOVA analysis. The sociodemographic variables that were included in this model were the gender and the number of years of drivinge experience. Nevertheless, these variables did not have a significant influence on the THW the participants took.

Secondly, the results from the driving simulator experiment, and mainly the observed behavioral adaptation of the MVs have been implemented in the VISSIM microscopic traffic flow simulation to test the impact of the four lane separation scenarios on the traffic flow. The traffic flow of these four scenarios with its corresponding behavioral adaptation have been tested under different circumcises: (1) the penetration rate of AVs; (2) traffic intensity; (3) the distance upstream of an off-ramp in which vehicles perform a lane change; (4) and the length of the weaving section in which AVs can enter or exit the dedicated lane. The results showed that a dedicated lane for AVs will have a positive influence on the traffic flow when a certain penetration rate of AVs is reached. Regarding the continuous Access Lane, the traffic flow is improved over the baseline scenario once a penetration rate of 15-20% is reached. While in the scenario of the Limited Access Lanes the traffic flow is improved at penetration rates around 30-35%. Furthermore, it appears that a dedicated lane is most beneficial with higher traffic intensities and that the current length for weaving sections is also sufficient for a dedicated lane.

Based on the results of this study, recommendations for the Dutch Road Authority (Rijkswaterstaat) were provided. With regard to the traffic efficiency a continuous access lane would be the most desirable once penetration rates of 15-20% have been reached, nevertheless a decreased THW of drivers of manually driven vehicles when there is no physical separation between them and the dedicated lane might threaten traffic safety. Therefore, safety issues should be extensively investigated in further research. This thesis sets the first steps for investigating the implications of a dedicated lane for AVs on highways traffic efficiency and safety in the Netherlands, but for actual implementation more research is needed.

Samenvatting

Het is de verwachting dat de komende jaren de druk op het wegennetwerk in Nederland zal toe nemen alsmede door toenemende urbanisatie. Een mogelijke oplossing voor alle problemen die gerelateerd zijn aan deze toenemende mobiliteitsvraag is de opkomst van automatische voertuigen. Het is de verwachting dat zij bij zullen dragen aan een verbetering van de verkeersdoorstroming, verkeersveiligheid en het milieu. Echter zal de daadwerkelijke implementatie van dergelijke voertuigen nog vele uitdagingen moeten doorstaan. Het is de verwachting dat door de lage complexiteit van het snelwegnetwerk, in verhouding met binnenstedelijke situaties, hier automatische voertuigen als eerste zullen worden uitgerold in de nabije toekomst. Echter, zijn er nog veel onduidelijkheden met betrekking tot de implementatie van autonome voertuigen en zal meer inzicht en kennis verkregen moeten worden om de infrastructuur toekomst bestendig te maken.

Een van deze onduidelijkheden is wanneer automatische voertuigen (AVs) gelijktijdig met manueel bestuurbare voertuigen (MVs) op de weg rijden. Verschillende onderzoeken refereren hierin naar een doelgroep specifieke rijstrook voor automatische voertuigen als de oplossing, echter is hier nog vrijwel geen wetenschappelijk onderzoek naar verricht. Om meer inzicht te krijgen in de implicaties van een dergelijke rijstrook en de invloed die het zal hebben op het rijgedrag van andere weggebruikers en de doorstroming op de snelwegen in Nederland is daarom de volgende onderzoeksvraag opgesteld: *"**Hoe wordt het rijgedrag van andere weggebruikers beïnvloed door de implementatie van een doelgroep specifieke rijkstrook voor automatische voertuigen op de snelwegen in Nederland en wat zijn de gevolgen hiervan op de doorstroming?**"*.

Om tot antwoorden te komen op deze onderzoeksvraag en inzicht te krijgen in de gevolgen van de implementatie van een doelgroep specifieke rijstrook op de gedragsverandering van bestuurders van manuele voertuigen en op de doorstroming zijn twee onderzoeksmethode gecombineerd. Eerst is er een rijsimulator onderzoek gedaan waarbij vier wegontwerpen voor de doelgroep specifieke rijstrook zijn ontwikkeld die verder zijn onderworpen aan onderzoek. Een baseline ontwerp, zonder een doelgroep specifieke rijstrook, een doelgroep specifieke rijstrook met continue toegang en twee rijstroken met gelimiteerde toegang van en naar deze rijstrook. Een is afgescheiden door een doorgetrokken witte streep, de andere is afgescheiden door een vangrail. Om meer inzicht te krijgen in de veranderingen in het rijgedrag van andere weggebruikers zijn alle vier de wegontwerpen getest in een rijsimulator. Hieruit bleek dat wanneer bestuurders van conventionele voertuigen in de nabijheid van een platoon van AVs rijden op de daarvoor bestemde rijstrook ze hun volgtijd verminderen. Uit een Repeated Measures ANOVA met een Greenhous-Geisser correctie bleek dat de verschillen in de gemiddelde aangenomen volgtijd significant waren tussen de vier verschillende wegontwerpen. De geobserveerde waarden wanneer een auto direct naast de doelgroep specifieke rijstrook reed waren significant lager dan wanneer de bestuurder en de AVs waren afgescheiden door middel van een vangrail. Verder is er een Linear Mixed Model toegepast om de Volgtijd van de bestuurder te voorspellen. Sociaaldemocratische factoren die hierin mee zijn genomen zijn geslacht en jaren rijervaring, echter bleken deze niet significant te zijn.

Vervolgens zijn de parameters die zijn geobserveerd in dit rijstimulator onderzoek toegepast in de VISSIM-verkeersmodellen om de doorstroming van de verschillende wegontwerpen te testen. De doorstroming met de bijbehorende gedragsverandering van manueel bestuurde voertuigen is getest met verschillende condities; verschillende penetratiegraden van autonome voertuigen, verschillende verkeersintensiteiten, verschillende afstanden waarop de voertuigen een rijstrookwisselingskeuze moeten maken en verschillende lengtes voor het weefvak. De inzichten die hierin zijn verkregen laten zien dat de doorstroming verbeterd wordt door de implementatie van een doelgroep specifieke rijstrook voor autonome voertuigen op het moment dat een bepaalde penetratiegraad wordt bereikt. Wanneer er een continue toegang is op deze rijstrook is er al een verbetering ten opzichte van de baseline op het moment dat 15-20% van de voertuigen autonoom is. Bij de wegontwerpen met een beperkte toegang, dus met een doorgetrokken streep of vangrail als scheiding tussen de doelgroep specifieke rijstrook en de reguliere rijstroken wordt de doorstroming pas verbeterd wanneer er een penetratiegraad van 30- tot 35% wordt bereikt. Verder is ook nog gebleken dat een dergelijke rijstrook gunstiger is bij hoge verkeersintensiteiten en dat een verlenging van de huidige lengte van het weefvak niet nodig is om de doorstroming te verbeteren voor een rijstrook voor autonome voertuigen.

Als laatste zijn er aanbevelingen voor Rijkswaterstaat aangeboden. Vanuit het perspectief van verkeersefficiëntie zal een doelgroep specifieke rijstrook voor autonome voertuigen gunstig zijn op het moment dat er een penetrantie graad van 15-20% is bereikt. Echter, zorgt een continue toegang van de autonome rijstrook ook voor een afname in de volgtijd bij bestuurders van manuele voertuigen. Deze afname aan de volgtijd door het gebrek aan een fysieke afscheiding kan mogelijk een negatief effect hebben op de verkeersveiligheid. Daarom is vervolgonderzoek op dit onderwerp aangeraden. Deze thesis zet de eerste stappen naar het onderzoek naar een doelgroep specifieke rijstrook voor autonome voertuigen op de snelweg in Nederland en de implicaties die daarbij komen kijken. Echter, om een dergelijke rijstrook daadwerkelijk te implementeren is er meer onderzoek om betere beslissingen te kunnen maken.

Abstract

Urban road traffic will increase in the upcoming years due to urbanization and it is expected that this trend will continue. Automated Vehicles (AVs), as one of the solutions, are expected to contribution to improve the traffic flow efficiency, traffic safety, and the environment. The implementation of AVs on highway is expected to be the most promising first step in the near future. One of the concerns regarding the implementation of AVs on highway is the mixed traffic situation, where automated vehicles and manually driven vehicles (MVs) drive simultaneously. Different studies suggest a dedicated lane as a solution to overcome these concerns. However, evidence-based research on the implications of dedicated lanes is still missing.

A driving simulator experiment to observe behavioral adaptation of drivers of manual vehicles exposed to different road design scenarios of a dedicated lane have been conducted. The results of this experiment are incorporated in VISSIM traffic flow models to test the influence of such a dedicated lane on the traffic flow. It appeared that drivers decrease their THW when they are driving directly next to a platoon of AVs while this was not observed when there was a guardrail separating them. With regard to a dedicated lane with a continuous access, the traffic flow is improved once penetration rates of AVs of 15- to 20% have been reached. For dedicated lanes with a limited access and thus specified entry- and exit ramps, the traffic flow is only improved for penetration rates of 30- to 35%.

The observed decreased THW of drivers of manually driven vehicles might threaten the safety when there is no physical separation between them and the dedicated lane. Therefore, safety issues should be extensively investigated in further research. This thesis set the first steps in investigating the implications of a dedicated lane for AVs on the highway in the Netherlands, but for actual implementation more research is needed.

List of abbreviations

ACC = Adaptive Cruise Control
AHS = Automated Highway Systems
AVs = Automated Vehicles
BL = Baseline
CACC = Cooperative Adaptive Cruise Control
CAL = Continuous Access Lane
CSV = Comma Separated Value
DRIP = Dynamisch route-informatiepaneel
h = Hour
Hz = Hertz
HOV = High Occupancy Vehicle
JSON = JavaScript Object Notation
Km = Kilometer
l = Lane
LAL = Limited Access Lane with buffer
LABL = Limited Access Barrier Llane
LV = Leading Vehicle
m = Meter
M = Mean
MVs = Manual Vehicles
s = second
SAE = Society of Automotive Engineers
Std. = Standard deviation
THW = Time headway
TRL = Transport Research Laboratory
US = United States
UNK = Unknown
V2I = Vehicle-to-Infrastructure
V2V = Vehicle-to-Vehicle
Veh = vehicle
VMS = Variable Message Signs
W99 = Wiedemann 99 Car following model
W74 = Wiedemann 74 Car following model

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1.0 Introduction

The road network in the Netherlands is near capacity (Ministerie van Infrastructuur en Milieu, 2017a). The congestion costs the country every year 2.5 billion euros (van Dijk, 2017), the European Commission already expressed their concerns regarding traffic related air pollution (EEA, 2014) and human errors cover more than 90% of the causes of vehicular accidents (Glancy, Peterson, & Graham, 2016).

With the growing population and urbanization, it is expected that these problems will be increased over the upcoming years (Ministerie van Infrastructuur en Milieu, 2017b). With the development of new technologies such as vehicle automation, these problems might be solved in a near future. Automated vehicles (AVs) represent a technological leap forward that can dramatically change how people approach mobility (Howard & Dai, 2014). It also expected that AVs will have positive benefits for the Dutch society and positively influence the traffic problems we face. It is expected to reduce congestion, accidents and fuel consumption (Fagnant & Kockelman, 2013; Rijksoverheid, n.d.-b). At higher levels of vehicle automation, the human factor, and thus the human error is taken out of the system which will result in these reductions. With strong believes in AVs potential benefits for a significant change in road mobility, the Dutch Government wants to take the lead in the development of AVs (Schultz van Haegen-Maas Geesteranus, 2016). Taking vehicle automation into account in the design, development and maintenance of the road network was explicitly mentioned in the coalition agreement (Rutte, van Haersma Buma, Pechtold, & Segers, 2017) of the current government. Besides the optimism of the government towards this technology, there are still uncertainties. A main concern is how to incorporate this technology into our daily lives to exploit the benefits. Automated driving is the most beneficial when the complexity of the environment is low. Therefore, implementation of AVs on the highway is expected to be the most promising first step in the near future.

To keep up with the technological developments in the field of automotive, the infrastructure will need to keep pace and adapt it physical and digital design (Isaac, 2016b). In order to be prepared for these developments, research about the infrastructure intervention is necessary. This thesis will explore the implications and effects of the implementation of a dedicated lane with regard to behavioral adaptation of manual vehicles as understanding the effects of this lane on the traffic flow of the highway system in the Netherlands.

Therefore, the main research question that will be answered in this thesis will be the following:

How is drivers' behavior influenced by the implementation of a dedicated lane for automated vehicles on the highway in the Netherlands and what are the implications on traffic flow efficiency?

1.1 Problem statement

Automated Vehicles (AVs) are expected to contribute to improve traffic flow efficiency, traffic safety, and the environment. It is expected as well to boost Europe's competitive strength, job opportunities and growth (Rijksoverheid, n.d.-a). Nevertheless, to actually make this happen an in-depth understanding and consensus is necessary on how to adapt the infrastructure to future mobility. One of the concerns regarding the implementation of AVs is the mixed traffic situation (Litman, 2017; Shladover, 2009). Different studies (Litman, 2017; Lumiaho & Malin, 2016; McDonald & Rodier, 2014) suggest a dedicated lane as a solution for the problems that might occur in this mixed traffic situation. However, evidence-based research on the implications of dedicated lanes on traffic flow efficiency and safety is still missing.

To make such a dedicated lane possible there are some aspects that should be investigated. An increase in efficiency on the highways in the Netherlands when a dedicated lane is implemented may dependent on a variety of factors. The first factor is the penetration rate of AVs. At which penetration rate is it necessary to dedicate one of the highway lanes to AVs to increased throughput and be able to justify the limitation of manually driven vehicles from using this lane. Secondly, it is important to investigate how the dedicated lane is implemented in the highway system and if this might influence the driving behavior of the other road users driving in the proximity of the dedicated lane. Therefore, another important aspect that should be investigated is how other drivers will adapt their behavior to a dedicated lane for AVs. It might be the case that the changes in the driving behavior of drivers of manual vehicles might causes an impediment to the traffic flow. A dedicated lane for the AVs might improve the traffic flow efficiency of the AVs but worsen the traffic flow efficiency of the traditional vehicles. Therefore, to test these impacts, and also the overall impact on the traffic flow and safety of both automated and conventional vehicles at different penetration rates, research is necessary to get more insight and make better decisions for the medium to long term highway infrastructure planning.

1.1 Main objective

The objective of this research is to get more insight into the implications of a dedicated lane for AVs with different penetration rates in the Netherlands. This thesis will focus on automated systems for passenger transport and truck platooning will not be included due to time and resource limitation. More insight will be provided into behavioral adaptation regarding a dedicated lane for AVs and how this will influence the traffic flow. This insight can help the Dutch Road Authority, Rijkswaterstaat, with the decision making for the medium to long term planning period.

1.2 Scientific and societal relevance

This research investigates the implications of a dedicated lane for AVs on the highway on the Netherlands. Not much research has been conducted on this topic and therefore this research directly contributes to the scientific literature. This thesis includes the behavioral change of manually driven vehicles in traffic flow models which distinguishes this study with other studies investigating the influence of vehicle automation on the traffic flow. Moreover, research regarding behavioral adaptation, safety and reaction time of drivers of AVs have been tested in multiple driving simulator studies but the effect of AVs on the other traffic is an aspect in this field that is still understudied.

Therefore is the scientific relevance of this study is to gain more knowledge on the implications and effects of the implementation of a dedicated lane with regard to behavioral adaptation of manual vehicles as understanding the effects of this lane on the traffic flow of the highway system in the Netherlands.

Regarding the societal relevance this thesis might also give some interesting insights. The impact automated systems will have on the infrastructure is still unknown. Although a dedicated lane for AVs is not supported by the Dutch Road Authority for the upcoming 10 years (Rijkswaterstaat, 2017b), this thesis might give more insights in the implications of a dedicated lane which policy makers can take into account and provide them with handles to make better decisions. This will have direct impact on society and contribute to the future of mobility.

1.3 Thesis outline

The structure of this thesis is organized as follows. This chapter gives a brief introduction to the topic, the defined problem statement and the objective of this research. The second chapter provides an extensive literature review. Insights have been provided on the technology of Automated vehicles, the relationship between AVs and the infrastructure and behavioral adaptation, Traffic flow modelling and the sociodemographic characteristics that influence driving behavior. Based on thorough review of the existing literature research gaps are identified in Chapter 3. Moreover, the definition of the research questions with the expected results and the conceptual framework that is used to provide answers to these research questions are formulated in chapter 3 as well. Based on the literature review and logic reasoning different road design scenarios are developed in chapter 4, these road design scenarios are used in the two types of research methodologies that have been conducted, a driving simulator experiment and VISSIM Traffic flow modelling.

To get the insight of behavior adaptation of drivers of manual vehicles in the proximity of a platoon, a driving simulator experiment is conducted. This experiment and the observed behavioral adaptations for the four developed road design scenarios is elaborated upon in chapter 5. The driving simulator results are incorporated in the traffic flow models explained in Chapter 6. This chapter outlies the different road design scenarios and the corresponding influence on the traffic flow under different conditions. The thesis ends with a conclusion and discussion in Chapter 7, which shows the relevant findings, scientific relevance, societal relevance, research recommendations and final recommendations for the Dutch Road Authority.

2.0 Literature review

This chapter outlines the most relevant parts of the literature in order to obtain a better insight into automated vehicles and the implications for the infrastructure. This chapter discusses literatures regarding the relationship between automated vehicles with the infrastructure, relevant driving simulator research, traffic flow modelling for automated vehicles and sociodemographic variables that influence driving behavior. The last section summarizes the literature and concludes this chapter.

2.1 Autonomous and Automated Vehicles

This section provides an introduction to automated systems and the terminology that should be used. Furthermore it provides insights in the benefits of AVs and a thorough literature review on studies conducted about the market penetration of AVs.

Automated driving applied on a large scale encompasses a wide range of technologies and infrastructures, use cases and business cases, and products and services. Some of these developments are currently happening, some may be distant, and some will depend on specific technical innovations or particular policy choices (OECD/ITF, 2015). Although there is still a lot of speculation about the future of these self-driving cars and the impact they will have on mobility, the technology is in high development. Shifting driving from human to vehicle is potentially disruptive both technologically and socially, opening new possibilities (Meyer & Beiker, 2014).

At the outset, it is important to clarify the concept of the vehicles that will be studied in this master thesis. The concept of autonomous vehicles is thus slightly different from automated vehicles. The terminology of Autonomous Vehicles is described as self-driving cars which are capable of sensing their environment and navigating roads without any human input. These vehicles are capable of making intelligent decisions about the vehicles' behavior and interaction with other road users by the use of technologies like GPS, Lidar and radar (Isaac, 2016a). Automated Vehicles are also equipped with these technologies but are also capable of communicating. Communication based vehicle systems include both Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle systems (V2V) and are capable of exchanging information and data. These cooperative functions make the distinction between Autonomous Vehicles and Automated Vehicles. This differentiation in terminology is clearly clarified by an analogy of Shladover, (2005) with human sensory capabilities. "The Autonomous Vehicle would be deaf-mute who retains vision while the cooperative vehicle would augment its vision with the ability to 'speak' and 'listen' to others." (Shladover, 2005).

To distinguish between different levels of automation and to simplify communication and facilitate collaboration within technical and policy domains, SAE developed a common taxonomy and definitions for automated driving (Figure 2-1). The levels 0-2 are the human driver levels and from level 3 the automated driving system takes over. The substantial difference between level 2 and level 3 is that in level 3 vehicles are able to monitor the driving environment around them. Crucially, these types of vehicles make decisions themselves and the human driver is solely necessary to intervene on request of the vehicle. Therefore, not all levels of automation include the capability to communicate with other vehicles. The vehicles that are already active on the Dutch road network are primarily level 2 of automation (CROW, n.d.).

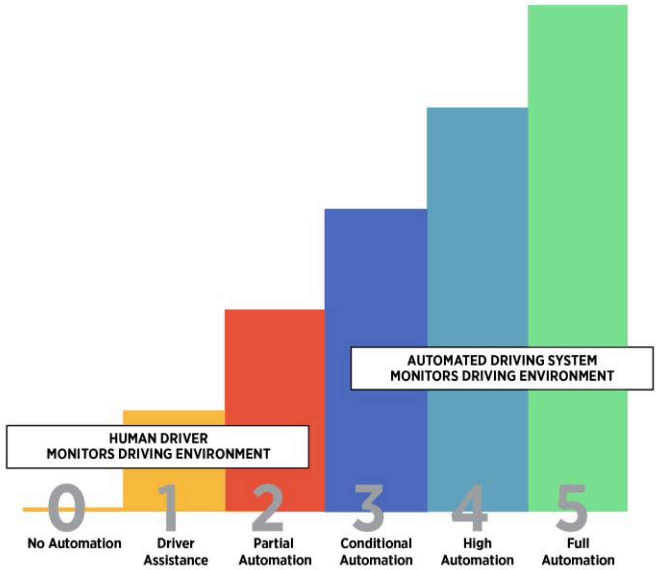


Figure 2-1. SAE levels of Automated driving (SAE International, 2014)

2.1.1 Benefits of AVs

These emerging technologies are very promising and multiple benefits are often mentioned. It is expected to reduce congestion, accidents and fuel consumption (Fagnant & Kockelman, 2013; Rijksoverheid, n.d.-b). These benefits are expected because congestion and accidents are mainly caused by human errors, and full vehicle automation takes the human and thus its mistakes out of the loop. Fagnant & Kockelman, (2015) translated these prospective benefits into annual economic benefits from AVs in the United States (Table 2-1). Furthermore, AVs will also have a social impact. With full automation, this technology could provide the elderly or disabled with the ability to move around independently. Another social aspect that could encounter change because of fully automated vehicles is the travel time appreciation. The time spend driving can be spend conducting other activities in the vehicle, which could completely change the way people approach mobility. These social impacts could have a disruptive impact on society as well.

Table 2-1. Economic benefits of AVs (Fagnant & Kockelman, 2015)

Market share of AVs	**10%**	**50%**	**90%**
Lives saved	1100	9600	21.700
Economic crash cost savings (B dollars)	5.5	48.8	109.7
Travel time savings (M hours)	756	1680	2772
Fuel savings (M liters)	386	848	2741
Annual savings: economic costs only (B dollars)	25.5	102.2	201.4
Annual savings: Comprehensive costs (B dollars)	37.7	211.5	447.1

Based on Table 2-1, it can be concluded that the higher the penetration rate of the AVs, the more benefits for society. The penetration rate and when a certain amount of AV penetration will be reached in the future is still speculative.

2.1.2 Market penetration of AVs

While high levels of uncertainty currently surround the estimations regarding the adoption time of AVs on the road network. Car manufacturers and software companies already have presented prototypes of self-driving vehicles and have announced their intentions to have commercially available AVs by 2020 (Fagnant & Kockelman, 2013). That the automotive industry is ready will not imply that our society is ready as well. Other factors such as consumer acceptance, government-, privacy, security regulations and insurance adjustments, may influence the penetration rate. If the technology is available does not imply people actually use this technology. It appeared that less than 20% of the drivers who have the possibility to use adaptive cruise control in their vehicle actually uses it (Connecting Mobility, 2017). Furthermore, results from a recent study showed that nowadays 72% of German consumers did not felt that fully automated vehicles would be safe (Deloitte, 2017). Therefore, consumer acceptance should be changed to make full adoption happen. Regarding the adoption of new technological inventions, the technology adoption curve (Figure 2-2 by Rogers, (1995)) is often referred to. This theory elaborates on the differences within society regarding the adoption of new technological innovations. The different prediction curves that are made by different institutions are also diverted from Rogers' curve.

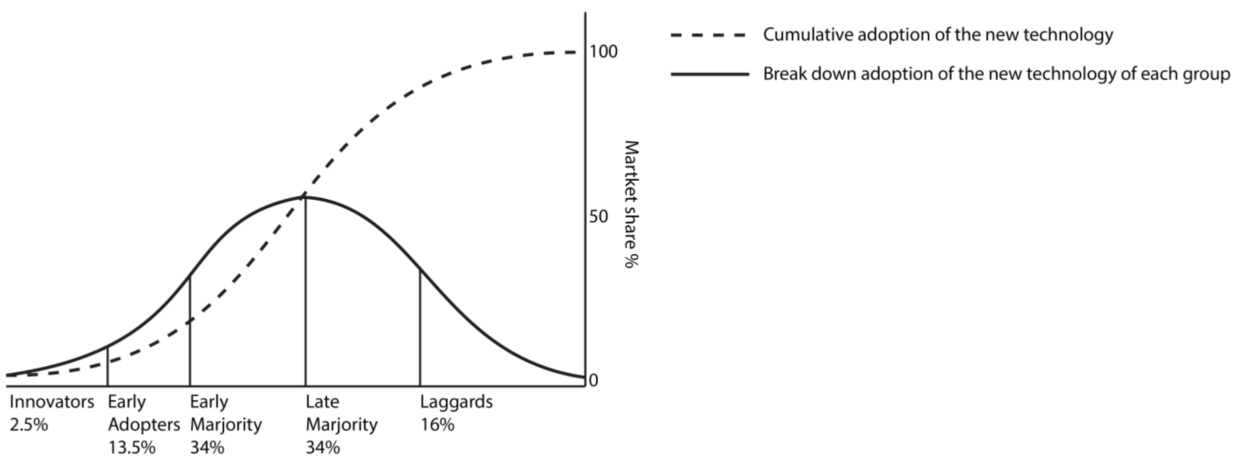


Figure 2-2. Rogers Technology adoption curve

Regarding the availability of AVs, results from a survey held among experts during the Automated Vehicles Symposium in 2014 showed that fully automated vehicles will be available on the market between 2018 and 2020 for conditional automation on freeways, and between 2027 and 2035 for full automation (Underwood, 2014). The Victoria Transport Policy Institute (Litman, 2014) is rater reluctant with their prediction about the adoption of the technology. The prediction is that in 2040, SAE level 4 and level 5 AVs will represent approximately 50% of the vehicle sales, 30% of the vehicles, and 40% of all the vehicle travel. Moreover, Lavasani, Jin and Du (2016) made a Market Penetration Model based on Bass diffusion models and previous technology adoption experiences, which is similar to Rogers' Technology adoption curve, and found that the market will be saturated in 2059 (Lavasani, Jin, & Du, 2016). IHS Automotive, (2014) has a similar estimation. They expect that SAE level 3 will be functional by 2020, level 4 by 2025, and level 5 by 2030, with AVs reaching 9% of sales in 2035 and 90% of the vehicle fleet by 2055.Both these predictions have a more steep increase in the penetration curve (Figure 2-3). On the contrary, Navigant Research and The Institute of Electrical and Electronics Engineers (IEEE) are more optimistic. Navigant Research anticipates the penetration rate of vehicles with automated driving modes on average will be about 4% of the global vehicle market in 2025, rising to roughly 41% in 2030 and 75% by 2035 (Alexander & Gartner, 2013). IEEE expects that by 2040 75% of the vehicle fleet will be automated (Tardo & Stickel, 2012). Furthermore, there are also some experts who express their skepticism and expect that level 5 will never be reached (Gomes, 2014). Nevertheless, besides the skeptics, most of the experts agree on the fact that AVs will be inevitable in the future and generally believe that driverless vehicles will be ubiquitous on roadways around 2035 – 2050 (Greenblatt & Shaheen, 2015). Most of the previously mentioned studies state that around 2050 market penetration will be around 80-100%.

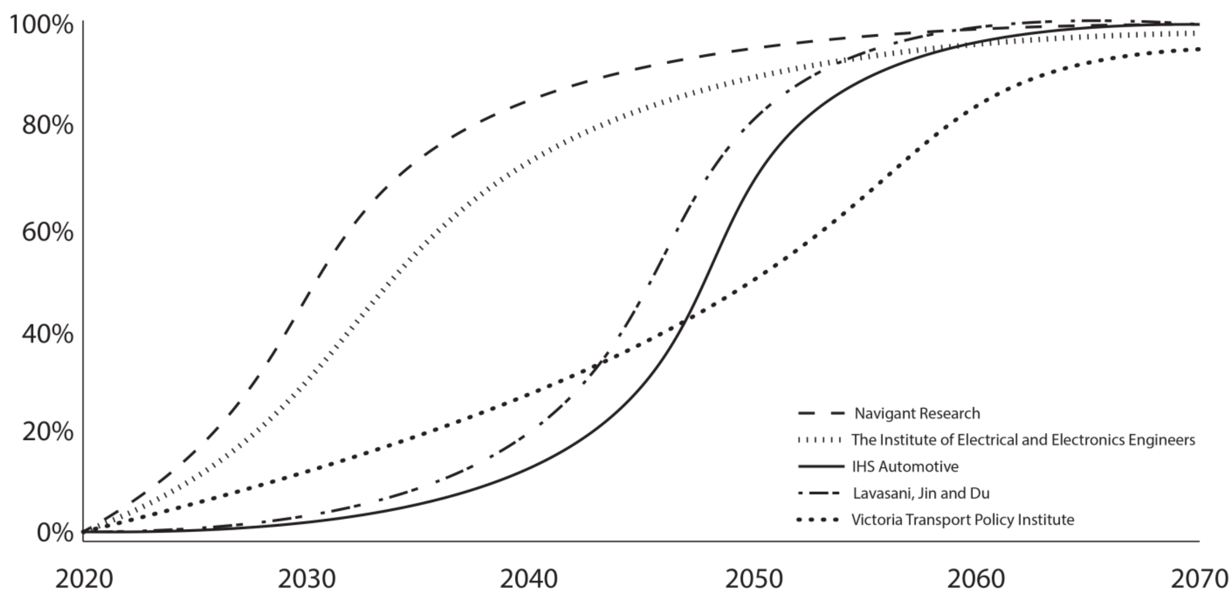


Figure 2-3. Penetration rate predictions AVs

As can be seen in Figure 2-3 the uncertainty gap from 2050 to 2070 is rather small and different knowledge institutions agree approximately on the penetration of AVs in this period, nevertheless the prediction in the upcoming period between 2020 and 2050 differs significantly and uncertainty is still predominant.

It is inevitable that AVs represent a potentially disruptive yet beneficial change to our transportation system and travel behavior. This potential impact is highly depended on the penetration rate of AVs. As a result of the connectivity of the vehicle, the higher the penetration rate of AVs the better the benefits of this technology could be exploited in terms of costs, safety and congestion reduction.

2.2 Automated Vehicles and the infrastructure

This section provides an introduction in the relation between automated vehicles and the infrastructure. When this relationship is explored, it is important to bear in mind that the government has an essential impact on the implementation of AVs. Besides the fact that it is crucial that the government proactively establishes policies and regulations for the deployment of AVs on the road network to ensure safety and mobility, the Road Authority also has a crucial role in the development of the infrastructure (Isaac, 2016b). The expectation is that AVs will be first implemented on highways and therefore the importance of the Dutch Road Authority (Ministry of Infrastructure and Water Management) in this matter should be emphasized.

Highway travel would change significantly with more automated vehicles on the road network in the Netherlands. According to Shladover, (2005) the most contentious issue associated with road vehicle automation involves the choice between mixing automated traffic freely with conventional non-automated vehicles or dedicating a special lane for automated vehicles. Different studies (Litman, 2017; Lumiaho & Malin, 2016; McDonald & Rodier, 2014; Milakis et al., 2017; Shladover, 2005) suggested the implementation of dedicated lanes for AVs as a solution for the difficulties that might occur in a mixed traffic situation. This makes it possible to benefit from the increase of the throughput per lane (Somers & Weeratunga, 2015). Once the penetration rate for automated vehicles reaches a sufficient number, it will be beneficial for the transport efficiency to create reserved lanes for automated driving. The benefits of automated vehicles can be maximized on a reserved lane due to the fact that the separated continuous flow of automated vehicles is not interrupted by non-equipped vehicles. (Friedrich, 2016). By emphasizing these benefits, the adoption of this new technology might also accelerate. Although the dedicated lane is often mentioned as a solution, research about the implementation and the design of these lanes is lacking and there are still uncertainties to overcome. Because of this lack of research and the fact that these lanes are not implemented yet it could be valuable to investigate similar cases to obtain knowledge and experiences. High Occupancy Vehicle (HOV) lanes are similar to dedicated automated lanes and therefore can be used as an example. The Netherlands once had a HOV lane in 1993, but this lane was converted to a reversible lane open to general traffic after a judge ruled that the Dutch traffic law lacked the concept of carpooling (Brandsma, 2000). Because of the limited use of HOV lanes in Europe, examples from Canada and the United states could be used as a reference.

About the actual design of the dedicated lane scientific research is lacking. Exploratory research has been conducted in the 90's in the field of automated highway systems (AHS). They explored fully automated vehicles operating on special highway lanes with support from the infrastructure (Ioannou, 1997). One of the three fundamental assumptions in this field was that "*Automated Vehicles must be physically separated from non-automated vehicles, operating in their own dedicated lanes*" (Shladover, 2008). With current knowledge it is clear that this not inevitably the case. Therefore, new studies with the knowledge of the state of the art technologies are necessary to provide useful insights about the design decisions of the dedicated lane for automated vehicles.

Furthermore, there is another problem regarding infrastructure adaptation for AVs that will always remain debatable, the problem with the chicken and the egg. In this case the adapted infrastructure would be the chicken and the AVs would be the egg. As mentioned, the role of the government has an essential impact. Is it the role of the Dutch Road Authority to take a more active role in the implementation of AVs into society by taking the lead and preparing the infrastructure for the technology, or should it be more passive and let the industry decide and let them take the lead? If the infrastructure is ready it might provide other road users with the opportunity to observe the efficiency of the technology, gain trust in the technology and therefore improve the adoption rate. Another possibility to accelerate the adoption rate is to use the executive power that the government has and generate incentives for road users to buy an automated vehicle instead of a manual vehicle. The other way around, when the Dutch Road Authority decides to take a more passive role, the infrastructure would be adjusted when there is an adequate amount of vehicles on the road. Nevertheless, considering the development time of road infrastructure and the adoption time of technology, the infrastructure might always be one step behind if the Government does not take action in primarily adapting the infrastructure.

Nevertheless, the principle of equality might be threatened when specific infrastructure will be provided for AVs in the primarily stage. Assuming that in this stage the technology will be expensive to such an extent that it isn't affordable for the middle-income, this would imply that a specific infrastructure would be constructed for the rich people of the society. Obviously, this is not a desirable outcome of a dedicated infrastructure and will be in conflict with the principal of equality. Therefore, further investigation on when a dedicated infrastructure would be beneficial is desirable.

2.3 Driving simulator research regarding Behavioral adaption to AVs

This section gives insights in behavioral adaptation in driving behavior research. Driving simulator research is a common methodology to test changes in driving behavior. In this section a small explanation about driving simulator research is provided together with the experimental designs of already conducted research on behavioral adaptation in the appearance of AVs. Furthermore, results of conducted behavioral adaptation research of the manual vehicle drivers in the appearance of platoons is explored.

In road safety research, Behavioral Adaptation is defined as an unintended or unexpected change in behavior that possibly is caused by a change in the traffic system. This behavioral adaptation might therefore also threaten safety benefits (Saad & Van Elslande, 2012). In order to conduct proper behavioral adaptation research in the field of driving behavior, research should be conducted carefully. Saad, (2006) also concluded that the underlying factors of behavioral adaptation are still not fully understood and more research with a careful methodology is needed to better understand them.

With regard to the behavioral adaptation due to the influence of automated systems the consideration of the temporally influence is emphasized. The introduction of automated systems may impact drivers' behavior, but the changes observed may develop as drivers first discover the system, learn all possibilities and limitations and become expert users. The high complexity of the human behavior and its behavioral changes makes it therefore very hard to adopt the values generated in other studies. Minor differences in the road infrastructure, physical or social environment might change the frame of reference and thus might result in behavioral adaptation. Consequently, tailor-made research methodologies might be necessary to test behavioral adaptation in infrastructure studies.

2.3.1 Validation of driving simulator research

For the last few years driving simulators became inherent in studying drivers' behavior research. The grade of reality is sufficient for testing driving behavior in laboratory research studies (Niezgoda, Kamiěski, Uciěska, & Kruszewski, 2011). Driving simulators are a suitable solution for testing how road design solutions are perceived and which driving behavior these solutions generate (Vienne et al., 2014). A validation study by Blaauw, (1982) showed similar effects of driving experience and task demands in an instrumented vehicle as in a driving simulator. Nevertheless, absolute values measured in the simulator produced significantly larger values than that the measured values in the instrumented vehicle. A study conducted by Mullen, Charlton, Devlin, & Bédard, (2011) showed simulator validity for the parameters speed and lateral position and a study by Risto & Martens, (2014) showed no significant difference between headway choice in the simulator and on a real road. Therefore, a simulator experiment for this research would be suitable to obtain the driving behavior parameters.

In order to obtain a proper grade of reality representation a distinction between low-, mid-, and high-level driving simulators should be made. A low-level simulator consists of a computer with a monitor and simple vehicle control system, such as a steering wheel and pedals. Mid-level simulators are more advanced and include a large projection screen, a more advanced vehicle with all normal controls and possibly a simple motion system. High-level simulators are the closest to reality and provide more or less 360 degree view and an extensive movement techniques (Weir & Clark, 1995).

When driving simulator research is explored in the field of AVs it appears that the conducted studies are predominantly focused on the human-machine interaction. These studies investigate the behavioral adaptation of the drivers who are driving the AVs (Merat, Jamson, Lai, & Carsten, 2012; Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Young & Stanton, 2007). Research regarding interaction between AVs and other road users is a topic that is not covered extensively. Gouy, (2013) conducted a study to get more insight in these relations and also used a driving simulator experiment, her findings will be elaborated in the following sections (2.3.2 and 2.3.3).

2.3.2 Experimental design of driving simulator studies on behavioral adaptation in the appearance of AVs

In order to learn from similar conducted research the experimental designs of these studies will be investigated. Gouy, (2013) conducted four studies using a driving simulator to test behavioral adaption in the appearance of AVs. In these studies participants drove behind a lead vehicle in the vicinity of automated platoons of vehicles exhibiting different headway characteristics. Further external factors were varied across the different simulator studies. The aim of her research was to investigate whether MVs adapt their car following behavior to the short THWs held in the platoons of AVs. An overview of the variation of external factors within these four studies conducted are shown in Table 2-2.

Table 2-2. Overview of the variation of external factors within the experiments of Gouy (2013)

	Study 1	Study 2	Study 3	Study 4
Simulator used	TRL's medium-fidelity driving simulator	low-level simulator, one front screen	TRL's medium-fidelity driving simulator	TRL's medium-fidelity driving simulator
Road	Three-lane highway	Three-lane highway	Three-lane highway	Three-lane highway
Conspicuity of platoon vehicle	Small, different vehicles	three-lane highway	Large, same vehicles	Large, same vehicles
THW of platoon	THW03 and THW10	Base Line, THW03 and THW10	Base Line, THW03 and THW14	Base Line (vehicles in 2.1s), THW03 and THW14
Participants	12	42, previously participated in driving simulators	30	30
Exposure time	11 min	6 min	16 min	Based on distance not time
information	Participants were not informed about the presence of a platoon			
Info:				Had to make an overtaking maneuver
Significance	no	no	Yes	yes

The environment Gouy, (2013) used in all the four studies was similar: A three-lane motorway separated by a double crash barrier in the middle with the platoon driving on the left lane of the road, this is thus similar to the highway in the Netherlands and thus the environment that would be used in the driving simulator research conducted for this thesis. Nonetheless, it should be mentioned that this research is conducted in the United Kingdom. Where the left lane on the Netherlands is the fastest lane, in the UK this is the slowest lane. The platoons in Gouy's (2013) study were driving exactly as fast as the leading vehicle in the first two studies, but in the 3th and the 4th study the leading vehicle was slowly taking over the platoons. Therefore, the platoons in Gouy's (2013) study were driving on the slowest lane.

In the first two studies by Gouy, (2013) a platoon of cars with a THW of 0.3s (THW03) was compared with a platoon with a THW of 1.0s (THW10). Within both studies a difference was found between the driving behavior of the MVs in both platoon scenarios, nevertheless these differences were not identified as statistically significant at the 95% confidence level. The third and the fourth studies, unlike the first two, found a significant difference in the driving behavior of the MVs in the presence of the truck platoons. In this study Gouy, (2013) compared a platoon with a THW of 0.3s (THW03) with a platoon with a THW of 1.4s (THW14). In the baseline measurement there wasn't other traffic besides the leading vehicle on the road. Another difference between the insignificant and the significant studies was the exposure time. The time participants were exposed to the platoons was 16 minutes instead of 6 minutes exposure. Results also showed that there is a significant difference in THW when comparing the period spent next to a platoon (Gouy, 2013).

The differences between the non-significant results in the second experiment and the significant results of the third experiment could provide insights regarding the factors that might influence the change in the frame of reference. Besides the THW and the exposure time, the type of vehicle was changed, in the third experiment. Trucks were used instead of cars to increase the saliency in the visual channel with platoons, and to increase the probability to allocate the attention of MVs to the platoon. Another change was the speed difference, the leading vehicle's speed was higher than the platoons' speed to enable the MVs to pass the platoons. Furthermore, the arrangement of the vehicles in the platoon differed in order to achieve an equal length in both platoons. These insights should be taken into account when the experiment is conducted for this Master Thesis.

Another insight that should be considered is an issue that occurred in the first experimental study of Gouy, (2013). The THW of the MVs that was measured in the driving simulator was computed with Cartesian distances instead of the real distance. In a Cartesian distance measurement the distance is measured between two points, in this case the measurement would not take curvature in the road into account. Another limitation was the familiarization of the participants of the experiment with the driving simulator, while previous studies concluded that it is crucial for the determination of the THW that drivers know their braking skills in interacting with a vehicle.

In the second experiment by Gouy, (2013) there were also some lessons learned to take into account when conducting a driving simulator experiment. These lessons learned focused on the incensement of the probability of drivers allocating their attention to platoons. In order to increase the salience of vehicle platoons, cars were replaced with Trucks, since trucks are more salient because of their outstanding shape. Furthermore, it was also noted that distances between vehicles might be more perceivable to non-platoon drivers if they pass platoons rather than driving next to it at a similar velocity. Finally, the low-level simulator used for the purpose of the present study merely offered a front vision. Using a medium-level simulator with side-views will certainly increase the visibility of the THWs within platoons. The simulator that was used in the experiments that appeared to be significant was a TRL's medium-fidelity driving simulator with a 210º horizontal forward field of view and a 60º rearward field of view. This difference in driving simulator makes it possible for the participants to observe the platoon more adequate. Therefore, a realistic simulator might thus also have influence on the results of a driving simulator experiment investigating behavioral adaption.

2.3.3 Observed behavioral adaptation in the appearance of AVs

Numerous studies (Al-Shihabi & Mourant, 2001; Naranjo, et al., 2008) attempt to mimic human driving behavior for automated vehicles(AVs), but how human driving behavior is influenced by automated vehicles has not been extensively investigated. Although researches on many different aspects of the road system have shown that drivers can react negatively to a change in the system, the implications of AVs on the human drivers are still understudied. Driving behavior is affected by road infrastructure, physical and social environment (Ram & Chand, 2016), any change in these factors might result in a change of their driving behavior.

A field study of the European project KONVOI, focused on quantifying the impact of automated systems on traffic operation and on the interaction between humans and vehicles. This project investigated the changes in the behavior of AVs' drivers and manual vehicles (MVs) drivers who overtook the truck platoon. The results show that drivers in the platoon who drove with a small time headway (THW) in a platoon significantly choose a shorter THW in the subsequent manually driven road section (Skottke & Debus, 2007). This carry-over effect resulting from the reduced THW changed drivers' behavior but did not change their judgement on a suitable THW, suggesting that behavioral adaptation can occur unconsciously. This reasoning lies in the theory that behavioral adaptation occurs through a change in the frame of reference (Helson, 1947). The observation of the small THW becomes unconsciously the reference they use in the decision-making process of their own THW. As a change in the frame of references seems to be responsible for the behavioral adaptation of platoon drivers to short THWs in platoons, it is reasonable to believe that this might also occur to MV drivers who have been exposed to platoons with short THWs in traffic.

Video data on the following distances of 1,500 vehicles that overtook the KONVOI vehicle platoon was collected. However, this data showed no significant difference between driving behavior while overtaking the platoon maintaining short distances of 10 m and the platoon with distances of 50 m between the vehicles (Lank et al., 2011). The following distance of the drivers was evaluated with time headway (THW) when approaching a leading vehicle. No significant effects were found when the effects of both scenarios were compared (Lank et al., 2011). Nevertheless, this short time observation of just one overtake per vehicle might not actually give insight into behavioral changes. Recently, Gouy, (2013) conducted a research about behavioral adaption of drivers of MVs to short time headways observed in a vehicle platoons.

Gouy conducted a simulator experiment, described in section 2.3.2, in order to test behavioral adaption in a more controlled environment. She found a significant difference in the driving behavior of the MVs in the presence of the platoons. The mean THW of the MV drivers showed that there was a significant difference between the platoons with a THW of 0.3s and the platoon maintaining a THW of 1.4s. They maintained on average a smaller THW in condition THW03 ($M = 1.87$, $SD = .18$) than in condition THW14 ($M = 1.99$, $SD = .17$). Therefore, it can be concluded that the presence of platoons of trucks maintaining short THWs in traffic have an influence on drivers' mean THW.

Based on the literature studies it can be concluded that there might be a behavioral change in the driving behavior of MVs in the vicinity of AV platoons. It can be concluded that behavioral adaptation to the short THW within platoons can occur in certain driving conditions. Based on these different studies it is still not clear under what conditions behavioral adaption may occur. The fact that it is still not entirely clear after the experiments conducted by Gouy, (2013) could lay in the critical issue that studying behavioral adaption is related to the diversity and variability of the road situations drivers encounter during a journey (Saad, 2006).

2.4 Traffic flow modelling and Automated Vehicles

Traffic flow modelling has the capability of predicting traffic volumes under certain circumstances on predefined infrastructural situations. This capability has been identified as a critical need for intelligent transportation systems in an operational setting (Smith & Demetsky, 1997). This section provides us with insights into studies regarding modelling MVs and AVs in VISSIM.

2.4.1 Micro simulation in VISSIM

VISSIM is a stochastic microscopic simulation model developed by PTV (PTV AG, 2015). It is a behavior-based multi-purpose traffic simulation to analyze and optimize traffic flows. It implements a psycho-physical car-following model and thus provides a very realistic driving behavior. It is widely used for simulating urban and motorway environments. Fellendorf and Vortisch, (2010) mention various applications for VISSIM and “Corridor studies on heavily utilized motorways to identify system performance, bottlenecks, and potentials of improvement.” is one of these applications. The complex model offers, but also requires, many parameters that need to be calibrated using measurement data from driving experiments. The model parameters can be adjusted to reflect different traffic situations (Fellendorf & Vortisch, 2001). The behavior of vehicles is based on several mathematical models, the position of each vehicle is recalculated every 0.1-1 s (Fellendorf & Vortisch, 2010b), which makes VISSIM very accurate.

2.4.2 Modelling MVs and AVs in VISSIM

In order to model the following behavior of drivers there are two following models present in VISSIM, Wiedemann 74 (W74) and Wiedemann 99 (W99). W74 model is suggested for use in urban traffic, while the W99 model is more suitable for freeway traffic (Arkatkar, 2016). The W99 is a model with an exceeding adaptability of the parameters to model driving behavior. Compared with W99, there are limited parameters with a possibility to adapt in the W74 model, which are the ‘average standstill distance’, the ‘additive part of safety distance’ and the ‘multiplicity part of safety distance’. These parameters for the car following model are thus solely based on keeping a safety distance, while the W99 also incorporates other parameters. In the W74 model it is not possible to adjust their THW, which is a crucial parameter for this research. Therefore, the W99 model is the most logical option for modelling the MVs in the traffic flow models.

The Wiedemann 99 car following model is a discrete, stochastic, time step based, microscopic model with driver vehicle-units as single entities (PTV AG, 2015) that can simulate traffic flow for micro simulation realistically (Fellendorf & Vortisch, 2001). The model is widely used in simulation research (Bierstedt et al., 2014; Motamedidehkordi, Benz, & Margreiter, 2016). This model is based on a situation with only manual vehicles and does not take into account the appearance of AVs which might result in behavioral adaptation.

It is clear that the W99 model is suitable for MVs, but to model the AV for traffic flow simulation there have to be some adaptions to the modeled driving behavior that is used for the MVs. Different studies tried to model AVs and used the W99 model as a basis. These are used as input for the parameter settings for modelling AVs in VISSIM. In a study by Aria (2016), VISSIM was used for investigating the effect of AVs. In this study it was assumed that all the AVs were highly automated and the assumption of connectivity was made. The parameters that were used in this model can be found in Table 2-3. Because of the Connectivity of the vehicles, which would also be the case in this study, the AVs were able to make cooperative lane changes (maximum speed difference of 3 km/h, maximum collision time of 10s) and advanced merging was activated. The study of Espinosa, (2017) assumed that the AVs that were modelled in her research were all with the same level of autonomy at level 3 with connectivity, thus automated vehicles instead of autonomous.

The lane changing models in VISSIM are deciding whether it is possible for a vehicle to change to the desired neighboring lane. In some cases this lane change is a free choice of the vehicle, when the 'slow lane rule' is applied the vehicles prefer to drive on the most right lane, or a mandatory choice of the vehicle, when it has to take a certain destination. This is based on the gap-acceptance of the vehicle and the related parameters. There is a parameter that defines for which accepted deceleration value a driver is willing to accept that he forces a lag vehicle on the desired lane to decelerate. For mandatory lane changes another parameter is of importance. This is the emergency stop position the vehicle takes when it has to stop before it has to reach a destination. The driver becomes more aggressive in their lane changing behavior when it comes closer to the emergency stop distance. Based on VISSIM Models presented in the literature these values do not differ for AVs and MVs. There is one option that difference and that is the option in the lane changing model to enable cooperative lane changes and this is a common feature for AVs modelled in VISSIM (Aria, 2016; Stanek, Huang, & Milam, 2017).

When the parameters that are used for modelling AVs as can be seen in Table 2-3 are compared, it becomes clear that the parameters used by Evanson & Lohmiller, (2017) are more extreme than the parameters used by Aria, (2016) and Espinosa, (2017). Therefore, a combination of the parameters, that can be seen in Table 2-3, would be the most suitable to simulate driving behavior for AVs in VISSIM. The parameters that were used in this study can be found in Figure 6-1-4 in section 6.1.4.

Table 2-3. Parameters used in VISSIM

Research	**(Espinosa, 2017)**		**(Aria, 2016)**		**(Evanson & Lohmiller, 2017)**	
Type Vehicle	MVs	AVs	MVs	AVs	AVs	MVs
Car following model	W99	W99	W99	W99	W99	UNK
Minimum look ahead distance (m)	0.00	150.00	0.00	150.00	0.00	UNK
Minimum look back distance (m)	0.00	150.00	0.00	150.00	0.00	UNK
Maximum look ahead distance (m)	250.00	300.00	250.00	200.00	250.00	UNK
Maximum look back distance (m)	150.00	200.00	150.00	200.00	150.00	UNK
Number of observed vehicles	2	10	2	7	4	UNK
Duration of temporary lack of attention (s)	0.00	0.00	0.5	0.0	0.00	UNK
Probability of temporary lack of attention (%)	0.00	0.00	1.00	0.00	0.00	UNK
Standstill distance (m) CC0	1.50	1.00	1.50	1.50	0.50	UNK
Headway time (s) CC1	0.90	0.50	1.05	0.3	0.4	UNK
Following variation CC2	4.00	1.00	4.00	4.00	0.00	UNK
CC3	-8.00	-8.00	UNK	UNK	-5.00	UNK
CC4	-0.35	-0.10	-0.30	-0.30	0.00	UNK
CC5	0.35	0.10	UNK	UNK	0.00	UNK
CC6	11.44	0.00	UNK	UNK	0.00	UNK
Desired acceleration starting standstill(m/s2) CC8	3.50	4.00	3.50	3.50	3.50	UNK
Oscillation Acceleration CC7	UNK	UNK	UNK	UNK	0.25	UNK
Desired acceleration at 80 km/h (m/s2) CC9	1.50	2.00	1.50	1.50	1.50	UNK
General behavior	UNK	Free lane selection	Slow lane rule	Slow lane rule	Free lane selection	UNK
-1 m/s2 deceleration per distance (own) (m)	UNK	100	300.00	300.00	1.00	UNK
Accepted deceleration (own) (m/s2)	UNK	-1.00	-1.00	-1.00	-1.00	UNK
Accepted deceleration (trailing) (m/s2)	UNK	-1.00	-0.75	-0.75	-2.00	UNK
To slower lane if collision time above (s)	UNK	-	15.00	15.00	-	UNK
Safety distance reduction factor	UNK	0.60	0.60	0.60	0.30	UNK
Maximum deceleration for cooperative braking (m/s2)	UNK	-3.00	-3.00	-3.00	-2.00	UNK
Advanced merging	UNK	V	-	V	V	UNK

Vehicle routing decision look ahead	UNK	V	UNK	V	V	UNK
Cooperative lane changing	UNK		-	V	-	UNK
Maximum speed difference (km/h)	UNK	3.00	-	3.00	-	UNK
Maximum collision time (s)	UNK	10.00	-	10.00	-	UNK
Both side is overtaking	UNK	UNK	-	-	-	UNK

2.4.3 The influence on the traffic flow

In order to understand how the traffic flow is influenced by AVs it is important to understand the current traffic flow first. The capacity of a traffic lane is determined by the maximum number of vehicles that can pass through a certain section per hour (Friedrich, 2016). It is determined by the density of the vehicle platoon and the speed with which the platoon passes through the section (Hoogendoorn, van Arem, & Hoogendoorn, 2014). The maximum traffic flow is determined by acceptable time gaps between vehicles, which has influence on the density of the vehicle platoon. In manual driving, the acceptable time gap is 1.64s according to literature (Nowakowski et al., 2010; Shladover, Su, & Lu, 2012). This is slightly under the 2 seconds rule, which is often used as a reference for safety. The acceptable time gap is determined based on the driver's safety perception. This includes his or her ability to observe, their reaction time, previous experiences and expectations about the behavior of other drivers, especially the driver of the leading vehicle (Shladover et al., 2012). Although the acceptable time gap is 1.64s according literature, the observed time gap in the Netherlands is 0.9s, which is much smaller (Swov, 2008). Furthermore is it assumed that the capacity for manually driven vehicles with a time gap of 1.64 is around 2200 vehicles per hour per lane (veh/h/l) (Hoogendoorn et al., 2014; Shladover et al., 2012).

When the traffic flow is based on the basic formulas (equation 1-2) of traffic engineering, it is a logical conclusion that the capacity should be improved with 100% AVs based on the decrease of the accepted time gap.

$$q = k \cdot v(k) \qquad [1]$$

traffic volume q (veh/h)
traffic density k (veh/km)
mean speed v (km/h)

$$k = \frac{1}{vT+L} \qquad [2]$$

Time gap to the preceding vehicle T (s)
Length of the vehicle L (m)

With full automation it seems logical that the time gap can be decreased, which would result in a higher traffic density with would result in an improved traffic flow. According to Friedrich, (2016) an increase of traffic volume to about 3,900 veh/h would thus be possible with purely automated traffic compared to the broadly assumed capacity values of a lane of 2,200 veh/h.

The technology that is primarily responsible for this decrease of the time gap and thus has the effect on the improvement of the total capacity and subsequently on the traffic flow is the implementation of Cooperative Adaptive Cruise Control (CACC). "*Cooperative ACC (CACC) is a further development of adaptive cruise control (ACC) that adds vehicle-to-vehicle communication, providing the ACC system with more and better information about the vehicle it is following. With information of this type, the ACC controller will be able to better anticipate problems, enabling it to be safer, smoother, and more "natural" in response. Although CACC is primarily designed for giving the driver more comfort and convenience, CACC has a potential effect on traffic safety and traffic efficiency.*" (Van Arem, Van Driel, & Visser, 2006). The decrease in time gap caused by CACC can be seen in Figure 2-4 (Nowakowski et al., 2010). The black line represents the cumulative distribution of drivers in MVs and their time gaps in observed situations. As can be seen in the figure 56.8% of the drivers have a larger time gap than within the CACC range and solely 7.6% of the observed cases have a smaller time gap.

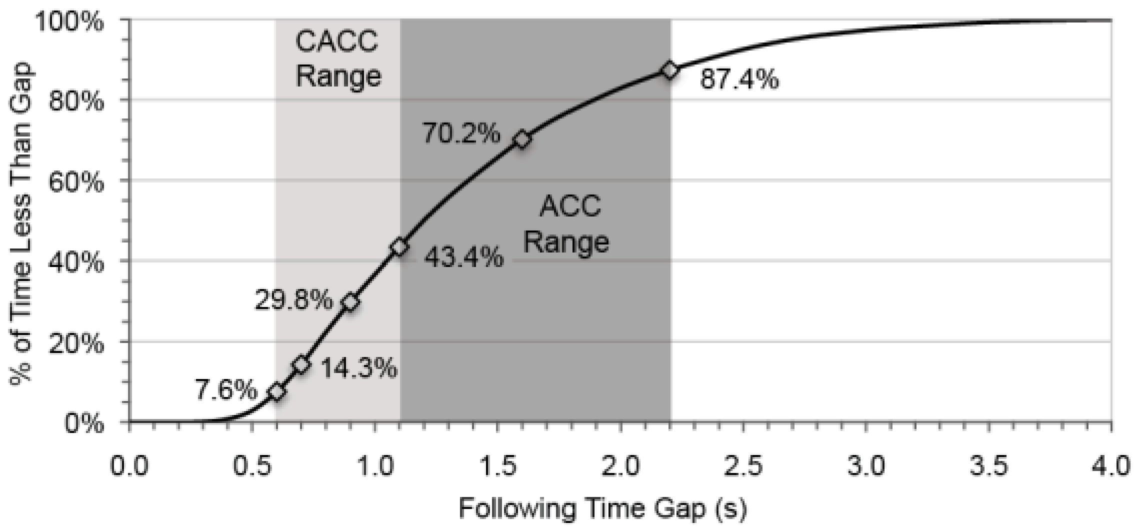


Figure 2-4. Cumulative Distribution of Following Time Gaps under manual driving (Nowakowski et al., 2010)

Nevertheless, the impact on the traffic flow is not solely based on the decrease of the time gap. CACC uses automated longitudinal control combined with inter vehicle communication which makes it possible to anticipate to braking maneuvers of cars in front. This makes it possible to anticipate in emerging shock waves that could be caused by the braking of a single vehicle (Orosz, Wilson, Szalai, & Stépán, 2009), with the aim of smoothening traffic flow and enhancing traffic safety (Van Arem, Tampere, & Malone, 2003). Thus, AVs have the potential to improve traffic flow by decreasing the time gaps between two vehicles and increase the traffic-flow stability by the non-existence of unstable small-amplitude oscillations that disrupt the uniform flow. This improved performance can merely be achieved when multiple vehicles have a CACC system and are able to communicate. Therefore, the improvement of the traffic flow largely depends on the penetration rate of AVs (Van Arem et al., 2006) as also stated in section 2.1.2.

Other studies also confirmed the improvement of the traffic flow as a result of this technology. In the situation with the availability of separated infrastructure and all vehicles are able to communicate with each other Ioannou, (1997) predicted that high capacity values of up to 8,500 vehicles an hour per lane can be achieved. A more recent study (Van der Werf, Shladover, Miller, & Kourjanskaia, 2002) investigated the results of three distinct cases with 100% manually driven vehicles, 100% ACC (time gap of 1.4 s), and 100% CACC (time gap of 0.5 s). It was concluded that CACC can potentially double the capacity of highway lanes with a high CACC market penetration from 2050 to 4550 veh/h/l. Furthermore a field test of CACC showed that if drivers were comfortable enough using CACC at a time gap of 0.5s, the capacity per lane could be increased to 4,400 veh/h/l if all vehicles were equipped with the system (Shladover et al., 2001; Van der Werf et al., 2002).

The value of 0.5s as a time gap is often used for CACC enabled vehicles (Shladover et al., 2001; Van der Werf et al., 2002). Nevertheless, it was concluded from an empirical field test that the actual preferred time gap is slightly different for CACC enabled vehicles: 12% Of the drivers preferred a time gap of 1.1 s, 7% at 0.9 s, 24% at 0.7 s, and 57% at 0.6 s (Shladover et al., 2012). This is also similar to the CACC range in Figure 2-4.

Shladover et al., (2012) had a more extensive study with different penetration rates of ACC, CACC and manual vehicles, and as well the time gap for CACC of 0.5s as the observed preferred time gaps. The model was developed in a way that in the CACC equipped vehicle can solely use its CACC capability when it is following another CACC equipped vehicle, but when it is following a manual vehicle it must revert to conventional ACC control.

He concluded that when basic ACC vehicles were incorporated into the traffic stream, the achievable traffic flow appeared to be remarkably insensitive to the market penetration of ACC vehicles, with flow remaining within the narrow range from 2,030 to 2,100 veh/h/l regardless of the market penetration. Only with the implementation of CACC equipped vehicles the traffic flow increases. The capacity grows slowly until the CACC market penetration becomes substantial, and then it grows more rapidly. If all vehicles are CACC equipped and the drivers chose the same distribution of CACC time gaps as they chose in the field test, the lane capacity would increase to 3,970 veh/h/l. The results were obtained using a micro simulation study conducted in AIMSUN, which is a hybrid simulation consisting of microscopic and mesoscopic levels, a dynamic traffic simulator, and macroscopic and static assignment models (Shladover et al., 2012).

Based on this literature review it can be concluded that traffic flow is expected to improve with the adoption of AV platooning, but this is highly dependent on the penetration rate and adoption curve of AVs. The increased capacity and the improvement of the traffic flow are partially caused by the reduction in THW or time gaps between two equipped vehicles as the absence of unstable small-amplitude oscillations that interrupt the uniform flow. This expected increase in traffic flow is as well based on studies with the presence of a seperated infrastructure or a scenarios of 100% CACC equiped vehicles as on a study based on the mixed traffic situation.

A dedicated lane for AVs would be a separated infrastructure but the real effect on the traffic flow is not as straight forward as it might seem. A dedicated lane on the left side of the highway might induce extra lane changing maneuvers which might also interrupt the uniform flow of the MV stream on the other lanes. A report conducted more than twenty years ago already emphasized these implications (Van Arem & De Vos, 1997). This assumption and the influence on the traffic flow were tested using the simulation model MIXIC 1.3 using multiple penetration rates of intelligent systems. Therefore, further investigating these merging implications for a dedicated lane would be desirable.

2.5 Driving behavior and sociodemographic characteristics

There is some research conducted regarding sociodemographic characteristics and the relationship with driving behavior (Peplińska, Wyszomirska-Góra, Połomski, & Szulc, 2015). This section synthezises on the most relevant research for this study.

Earlier studies show that there is a relationship between sociodemographic characteristics and road accidents. Young males tend to be more involved in risky driving behavior (Bener & Crundall, 2008), which would already imply that interesting sociodemographic characteristics to inspect are age and gender. An analysis of Peplińska et.al.,(2015) revealed that among a variety of sociodemographic variables age, gender and the duration of having a driving license were statistcally significant with the dangerous driver syndrome. There are multiple studies concerning age and gender as variables that influence driving behavior regarding accidents, risk perception and traffic violation. Therefore it would be logical to assume these sociodemographic factors might influence the THW as well. This is confirmed with a study investigating following gaps also found significant differences regarding gender and age (Rajalin, Hassel, & Summala, 1997). Another study investigating overtaking behavior also found significant differences in following gaps regarding gender and age (Farah, 2011). Nevertheless, studies testing the influence of driving experience on following behavior (Lewis-Evans, De Waard, & Brookhuis, 2010) or the THW (Winsum, 1996) did not find a significant relationship.

In conclusion, there might be different results in research regarding regarding the influence of socio-demographic characteristics on the THW. Neverheless, that there is an influence of these variables on driving behavior and more specific following behavior can not be doubted. Therfore these variables will be investigated in this research.

2.6 Conclusion and discussion

In the aforementioned literature the differences between autonomous- and automated vehicles have been defined and that this research will focus on automated vehicles due to the cooperative functions that are implemented in automated vehicles is stated. Insights have been provided in the market penetration of these technologies, but a clear answer is still not available yet. The uncertainty gap from 2050 to 2070 is rather small and different knowledge institutions agree approximately on the penetration of fully automated vehicles in this period (between 80-100%). However, the prediction in the upcoming period between 2020 and 2050, which is so important, differs very much and uncertainty is still predominant. This uncertainty is an unfortunate conclusion since the implementation of a dedicated lane and the potential benefits of AVs are highly dependent on this penetration rate. These potential benefits have also been expressed in the literature regarding the efficiency of the road network. This increase in efficiency is mainly due the decrease in accepted time gap between the vehicles. It is assumed that AVs can drive with a THW of 0.5s while regular traffic drives with a THW of 1.64s (according to literature) or 0.9s (measured in the Netherlands). This decrease in time gap is expected to have a potential benefit in increasing the traffic flow. This increase is expected under the assumption of a mixed (AVs and MVs) traffic situation but the potential benefits would be even more exploited when there would be a dedicated infrastructure for AVs.

Regarding the relationship between automated vehicles and the infrastructure, it cannot be ignored that the government will play a crucial role in the further development of this new technology and its consequences. The single most contentious issue associated with road vehicle automation involves the choice between mixing automated traffic freely with conventional non-automated vehicles or dedicating a special lane for automated vehicles. Multiple reports and studies suggested the implementation of dedicated lanes for AVs as a solution. Extensive research about this topic has not been conducted yet. Quite a lot of research regarding automated highway systems or dedicated lanes is conducted in the late 90’s, but thorough research about the actual impacts of such a lane with the knowledge of the current state of the art technology is lacking.

When behavioral adaptation regarding driving behavior was reviewed it was concluded that a previous study found significant differences in THW of manual driving when they drive in the appearance of a platoon of AVs. This was tested with truck platooning and with a road scenario where the platoons drove on the slowest lane instead of the fastest lane. Nevertheless, it might still be reasonable to assume that similar behavioral adaptation might be discovered if the AVs drive on the fastest lane. The lessons learned from four different experiments conducted in the literature regarding efficiency, behavioral adaptation and the significance of results will be taken into account for the development of the methodology for this experiment. Regarding the behavioral adaptation of driving behavior, it is important to conduct this type of research very carefully because of the underlying factors of behavioral adaptation are still not fully understood. Furthermore, it appeared that besides the behavioral adaptation because of the appearance of platoons, the socio-demographic factors of the driver might also influence their driving behavior. Factors such as gender and age have been identified as influential factors that should be taken into account.

Another important research question that came to light in this section is the insights in the parameters that are commonly used for traffic flow modelling for AVs and MVs. Insights have been provided in parameters that have been used in other studies as well as well for AVs as MVs.

Based on this literature review it seems that a driving simulator study using a high- or medium fidelity driving simulator is the most suitable research tool for investigating behavioral adaptation regarding the appearance of platoons for different road design scenarios of a dedicated lane. The software tool VISSIM is emerged as a very suitable tool for testing traffic flow influences this type of road scenarios.

Obviously it should also be stated that the research conducted by Gouy, (2013) is an indication that there might be behavioral adaptation when there are platoons of AVs near manual drivers. However, whether there are actual differences for different road scenarios is not clear and should be tested in a driving simulator study. These assumptions on behavioral adaptation are also based on one study conducted by Gouy, she extensively studied the effects of platooning but there are still uncertainties that aren’t answered yet, especially considering the high sensitivity of driving behavioral adaptation research.

3.0 Research Gaps, Questions and expected Results

A literature review has been conducted and this chapter will focus on the identified research gaps, the research questions that are formulated for this thesis and the corresponding expected results. These are elaborated in section 3.1, 3.2 and 3.3. Furthermore, the conceptual framework, that gives insight in the research process is explained in section 3.4.

3.1 Research gaps

Based on the literature review there are some research gaps that could be identified. One research gap is the uncertainty about the penetration and adoption rate of AVs. As indicated, a lot of predictions have been done but the actual penetration is still unclear. Obviously is it debatable if there ever will be a decent prediction regarding the adoption of new technologies.

Moreover, there are still a lot of uncertainties about the adoption of AVs in society. The direct costs and benefits have already been quite clear identified, but the effect on urban mobility still needs to be further explored. As Farah (2016) mentioned the scientific knowledge with respect to the physical infrastructure is relatively scarce compared to the digital infrastructure. Some research is conducted on this topic (Langton & Mcarthur, n.d.; McDonald & Rodier, 2014; Morsink, Klem, Wilmink, & de Kievit, 2016; Somers & Weeratunga, 2015) nevertheless the impact of AVs on the physical infrastructure is understudied. With regard of the infrastructural changes that are necessary for accommodating AVs on our road system there are still multiple research gaps to be answered. Aspects that are still unclear is the impact of AVs on lighting on the highway systems, emergency stop zones or the current standard for road curvature (Farah, 2016). Furthermore, the actual design decisions that have to be made for a dedicated lane are understudied, a clear answer on how such a lane should look like is lacking. Besides this, research regarding the implications of a mixed traffic situation is also lacking.

For the mixed traffic situation there are some studies suggesting a dedicated infrastructure for AVs (Litman, 2017; Lumiaho & Malin, 2016; McDonald & Rodier, 2014) nevertheless actual scientific research about such a lane is still lacking. With respect to this there are multiple research gaps to identify. Examples might be the design of such a lane, the merging sections, implementation costs or influence on other road users. The principle of the dedicated lane in itself is also an interesting subject for research.

3.2 Research questions

Based on research gaps identified in previous section, this thesis will try to solve following research questions.

How is drivers' behavior influenced by the implementation of a dedicated lane for automated vehicles on the highway in the Netherlands and what are the implications on traffic flow efficiency?

To support this main research question the following sub research questions are formulated:

- How should a dedicated lane for automated vehicles be designed? On which side of the road? Completely separated or not? What is the state of the art on this topic?
- How does drivers' behavior of the human-driven vehicles will be influenced when driving in proximity to a dedicated lane (of different characteristics) for automated vehicles?
- Which socio-demographic characteristics have influence on the THW?
- Which parameters in the car-following and lane-changing models need to be calibrated to simulate mixed traffic?
- At which penetration rate of AVs will the traffic flow be improved by the implementation of a dedicated lane?

3.3 Expected results

By conducting such a research, it is expected to get more insight into the complications and impacts of a dedicated lane for automated vehicles on the driving behavior of other road users and the implications on traffic flow efficiency. The output of this research will answer the question which infrastructure design scenario is the most optimal, how other road users will react to such a lane and at which penetration rate of AVs the change in the infrastructure design will be desirable for which scenario.

The hypothesis is that people will adapt their driving behavior when driving in proximity to a platoon on a dedicated lane by reducing their THW. The expectation is that this effect is bigger when they drive directly next to a platoon, while the effect is less when they are separated by a physical barrier.

The other expected result is that the traffic flow will be improved the most under the scenario of the continuous access lane. This is based on the fact that in this scenario no bottlenecks can occur in the entry and exit points of the dedicated lane because traffic can merge in and out of the dedicated lane when desirable. The expectation is that the traffic flow will be improved when a penetration level of 30% will be reached. This is based on the fact that 33.3% of all the vehicles will drive on one lane. Furthermore, the expectation is that age and gender will also have influence on the THW.

3.4 Conceptual Framework

This section outlies the conceptual framework that is used in this research. The objective of this research is to get more insight on how drivers' behavior and traffic flow are influenced by the implementation of a dedicated lane for automated vehicles on the highway in the Netherlands. To get more insight into this complex problem the combination of the design of the dedicated lane, a driving simulator study and traffic flow models were implemented in this research.

Firstly, the design of the dedicated lane was explored in chapter 4.0 which resulted into four different road design scenarios. In the driving simulator experiment more insight into driving behavior adaptation of the drivers of manual vehicles (MVs) regarding different road design scenarios of the dedicated lane was obtained. Moreover, these observed values were translated into parameters for the traffic flow modelling. Both these studies are outlined in chapter 5.0 and 6.0 of this thesis. Chapter 5.0 describes the driving simulator experiment and chapter 6.0 explains the traffic flow models.

A conceptual framework is developed to give more insight in the relationships within the entire research and how all these aspects will contribute to provide answers to the defined research questions, this is presented in Figure 3-1.

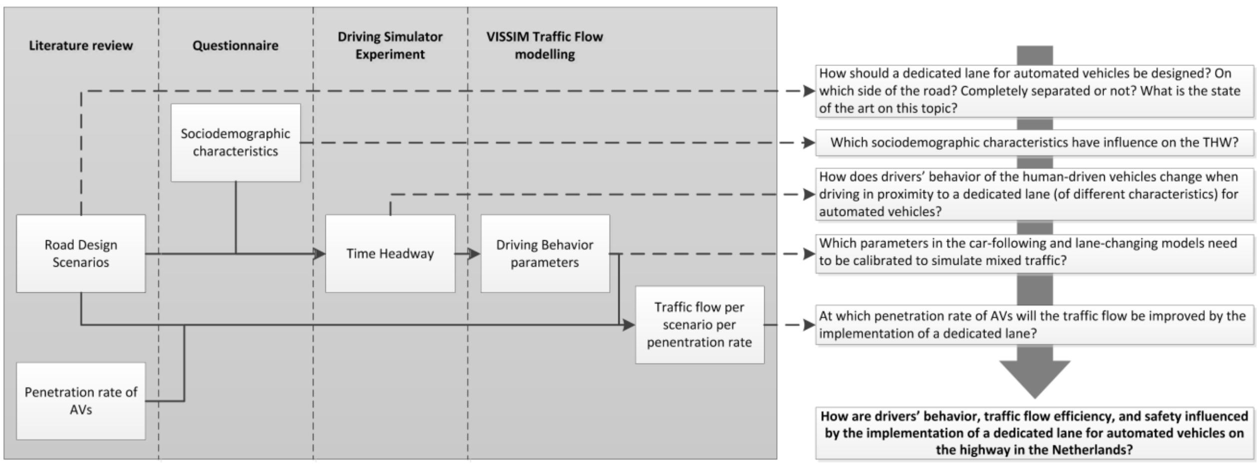


Figure 3-1. Conceptual Framework of this thesis

The main variable that is investigated in this research regarding driving behavioral change is the time headway (THW) drivers adopt within the different scenarios, which is measured in the driving simulator experiment. The time headway of drivers of MVs is influences by the road design scenarios and the Socio-demographic characteristics of the driver. This observed change in THW results in a change in the driving behavior parameters in VISSIM Traffic Flow modelling which influences, together with the road design scenarios and the penetration rate of AVs the traffic flow. This results in different traffic flows per scenario per penetration rate. These results provide the Dutch Road Authority with insights in the implications of the implementation of a dedicated lane for AVs.

4.0 The design of the dedicated lane

Regarding the design of a dedicated lane there are different aspects that could be evaluated and decisions to be made. The position of the lane, the level of separation of the lane and the type of separation of the lane are examples of these aspects. Due to the limitations of time and resources, the width of the lane is not included in this research. The exclusion of this aspect is based on the assumption that as long as there are still MVs on the road the lane width cannot be diminished. Furthermore, only lane width limitation for all the lanes would result in enough capacity to create an extra lane, which would not be the case in this research (Pielage et al., 2016). Therefore, this aspect is not taken into account in the design of the dedicated lane. In this chapter the design choices will be further elaborated and a deeper understanding of the different possibilities will be provided.

4.1 Position of the dedicated lane

One important aspect of a dedicated lane is its position in relation to the other lanes where traditional vehicles drive. It is mentioned in numerous reports that the lane would be positioned at the far left side of the road (Pielage et al., 2016; Schultz van Haegen-Maas Geesteranus, 2016). The HOV lanes in the US and Canada, which in some way can also be considered as a dedicated type of lanes, are also positioned on the left side of the road (Department of Transportation Division of Traffic Operations, 2016). Therefore, choosing the left lane as the dedicated lane for automated vehicles would be in line with drivers' expectations. Nevertheless, specific Truck lanes, which are also applied on the Highway in the Netherlands (A16, A20 and A50), are located at the right side of the road. The left side would be a logical position based on the assumption that the throughput of an automated lane would be higher than the throughput of regular lanes (i.e. lanes for traditional traffic). This would also be consistent with the positioning of truck lanes on the right side of the road. In order to take all the possibilities regarding the positioning of the automated lane into account a schematic representation of the three possible scenarios is described in Figure 4-1.

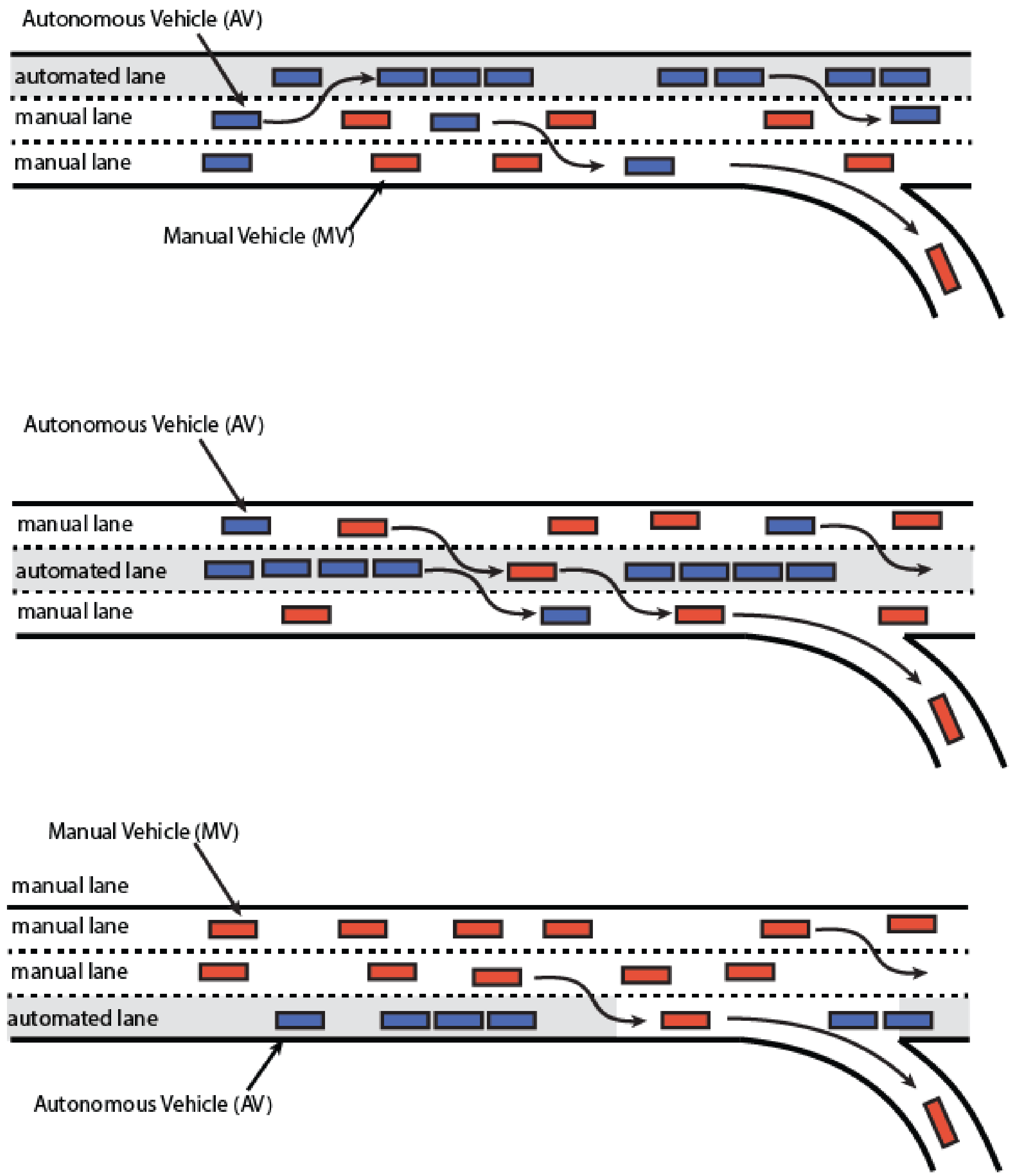


Figure 4-1. Possible scenarios regarding lane positioning

The far-left side of the road makes it possible for manual vehicles (MVs) to merge through traffic, make lane changing maneuvers and take the highway exit, without interfering with the automated lane. This is possible because the highway exit is predominantly positioned on the right side of the road in the Netherlands. Furthermore, this makes it still possible for AVs to merge out of the lane into regular traffic and take the exit of the highway. When the automated lane is positioned in the middle of the highway it makes it possible to merge into the lane from the left, as well as the right side. Nevertheless, choosing the middle lane might be an unattractive position since it could tempt other road users to merge into the automated lane and follow a platoon. The third option with the automated lane on the outer right side of the highway, makes it possible for AVs to merge through traffic, make lane changing maneuvers and take the Highway exit without intervening with the regular traffic. For the MVs the same is applied, besides they have to interfere with the automated lane if they want to exit the highway as can be seen in Figure 4-1.

In the literature the positioning of the automated lane on the left side of the road is often mentioned (Hall & Caliskan, 1997; Ran, Leight, & Chang, 1999; Tsao, Hall, & Shladover, 1993). Nevertheless, scientific research about the reasoning behind the positioning of the automated lane is lacking. For comparable infrastructure designs, like the HOV lanes, scientific reasoning behind the positioning of the lane on the left side of the road is also unavailable. Therefore, the reasoning behind the positioning of the lane could be merely substantiated with logic reasoning and common sense. Figure 4-1 supports this reasoning and underpins the theory that the left side of the road is the most suitable location for a dedicated lane for AVs.

4.2 Access of the dedicated lane

Another issue to consider when designing a dedicated lane is its access from the other regular lanes. Regarding the access there are two possible options, either a continuous access or a limited access to the dedicated lane. Continuous-access allows eligible vehicles to enter or exit the dedicated lane continuously from the other regular lanes, such that the lane changing maneuvers are not specified at a specific location along the road, there is thus no separation (Jang et al., 2009). The limited-access lanes have specified ingress and egress locations that permit lane-changing maneuvers to the dedicated lane and are separated from the other highway lanes by buffer zones or barriers. The reason for this separation is to allow less interruptions in the traffic flow and offer protection to freely flowing traffic in the dedicated lane (Jang et al., 2009). This separation is also supported by the theory of Automated Highway systems, where they support to erect barriers between the lanes because of concerns of collisions (Hitchcock, 1991; Tsao et al., 1993). These concerns of collision of safety would be contradicted by a study (Jang et al., 2009) about safety issues of HOV-lanes in Canada. This study shows that HOV-lanes with limited access offer no safety advantages over those with continuous access. With regard to the concern about traffic flow interruption, lane changing AVs do not necessarily lead to traffic flow interruption. The Vehicle-to-Vehicle (V2V) connectivity can avert noteworthy interruptions since connected vehicles can anticipate on a merging vehicle. Another aspect that should be pointed out is that when all the merging maneuvers are concentrated on specified entry- and exit ramps a bottleneck around these ramps might occur (Lay, Mchale, & Stevens, 1996).

When the dedicated lane is not physically separated from the other regular lanes, there is no difference with a regular lane regarding the lane changing possibilities. AVs as well as MVs have the possibility to change lanes whenever is most suitable, MVs are just not allowed to enter the automated lane. The road would in this case look like the situation in Figure 4-2**.** This schematic road layout shows the platoons driving on the outer left lane with the possibility to merge into traffic whenever necessary and the MVs driving on the other lanes. Vehicles can already turn on their automated system before entering the lane and using these systems for cooperative merging. When they enter the lane while the AV-system is enabled merging would be less disruptive because of the V2V connectivity of the AVs.

Another issue regarding the 'no separation' of the lane is the assumption that the system does not have any failure. In a situation that transition of control takes place and the vehicle has to set back from level 4 of automation to level 2 of automation there is no possibility for the driver to leave the automated lane in a situation with a separated infrastructure.

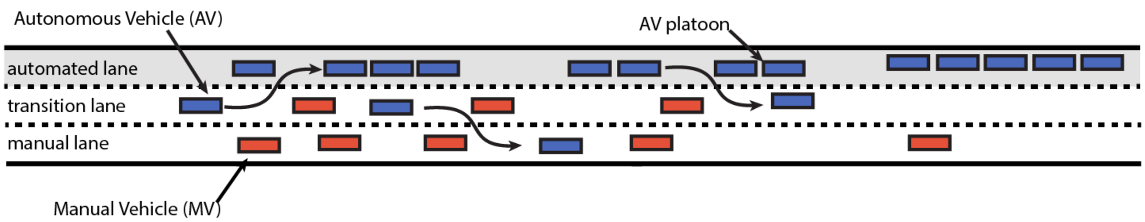


Figure 4-2. Segment of Continuous access lanes

Regarding the limited access lanes there are multiple options possible. One possibility, mentioned by Yim et al., (1997), is a separated lane with an transition lane that provides the possibility to check if vehicles are equipped. In this situation a minimum of lanes for manual vehicles would be necessary to enable passing maneuvers among faster and slower manually operated vehicles. This restriction would be hard to meet on the current highway system of the Netherlands since most of the highways in the Netherlands consist of 2 or 3 lanes in each direction. After all vehicles have entered the highway under manual control AVs intending to travel on the dedicated lane would primarily enter the transition lane under manual control. After examining the suitability of the vehicle, the eligible vehicle would enter the dedicated lane when a merging gap would be available. Vehicles which have to exit the dedicated lane will follow the reversed procedure. The schematic representation of the entry- and exit ramp of the dedicated lane with a transition lane proposed by Yim et al., (1997) is shown in Figure 4-3. In literature it is proposed that entry ramps should be located with a distance of approximately 3.5 km and exit-ramps should be located approximately 2 km after the entry ramp to provide adequate space for vehicles to properly execute entry and exit maneuvers (Delco, 1994). It should be noted here that drivers who want to exit the highway need to exit the dedicated lane far enough upstream of the desired highway exit.

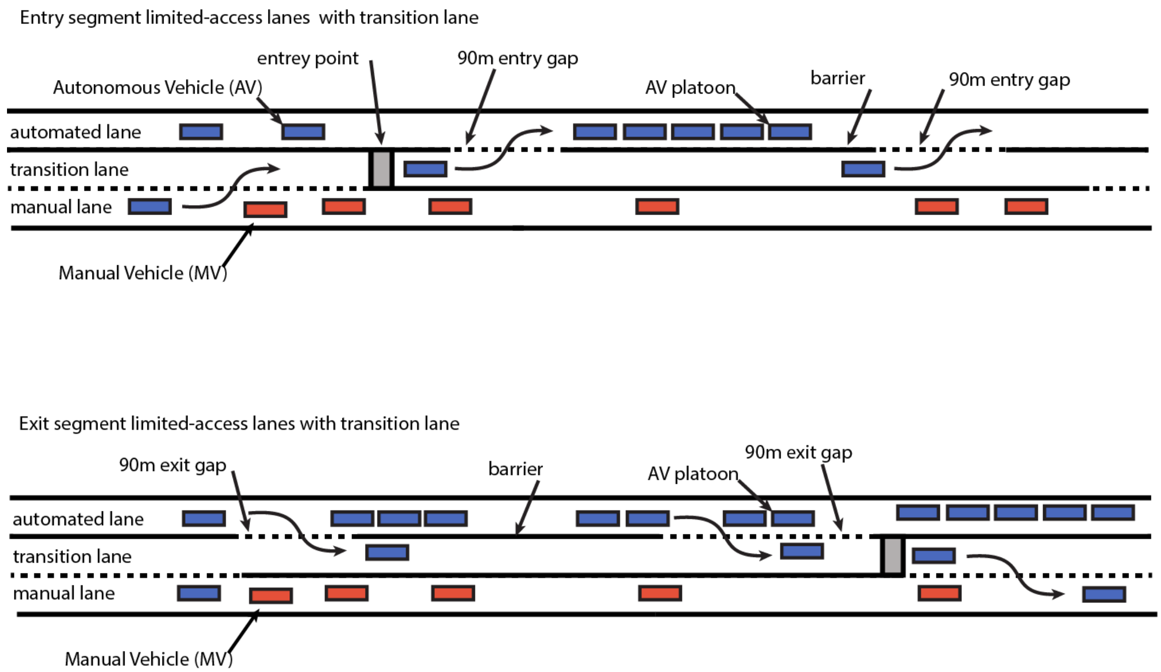


Figure 4-3. Exit and Entry segment limited-access lanes with transition lane

This road design is based on the uncertainty and dangerous situation that might occur when an unequipped vehicle will enter the automated lane. If all the other vehicles are well equipped with sensors that perceive their entire environment it does not necessary, have to become a dangerous situation when an unequipped vehicle enters the lane. Obviously, it is not desirable when an unequipped vehicle enters the lane. This could also be prevented with education, regulations and enforcement. This makes it possible to eliminate the checking points on the transition lane in the road design.

Another possible design that is based on a separated infrastructure is derived from this model but with the exclusion of the transition lane and checking points. It would imply a separated lane with an ingress–egress area every 3.5 km. In the highway system of the Netherlands this is more common and would be referred to as a weaving section[1] (Figure 4-4). It is a combination of an entry- and exit ramp which is normally used for entering or exiting the highway and is also often used in a Cloverleaf interchange.

[1] Weefvak

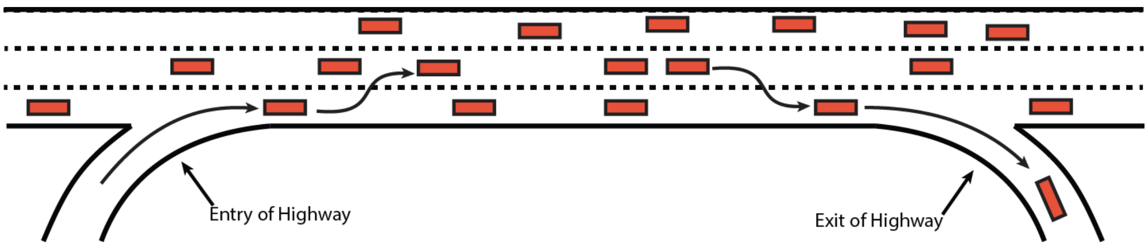


Figure 4-4. Weaving section

The schematic design of the road shown in Figure 4-5 makes it first possible for AVs to enter the dedicated lane and after this it is possible to exit the dedicated lane and enter the lanes for MVs. With this road design it is important to prevent MVs to enter the dedicated lane. Therefore, it is important to have clear road marking and signaling.

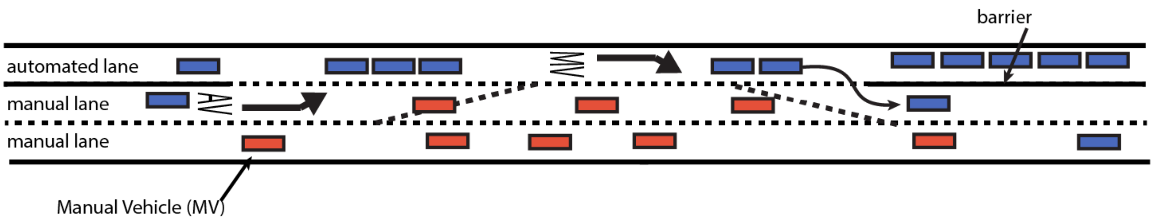


Figure 4-5. Segment limited-access lanes without transition lane

Literature indicates that a separation of the AVs with the MVs would be desirable with regard to the safety perspective, nevertheless research indicates that traffic safety is not at stake with a limited access lane. Limited access lanes might generate bottlenecks at the ingress and egress locations, but this might be overcome with the V2V connectivity of AVs. This connectivity can avert noteworthy interruptions since connected vehicles can anticipate on a merging vehicle. Therefore, both scenarios should be tested in this research.

4.3 Type of separation of the dedicated lane

Regarding the separation of the automated lane, if it appears that a separation would be desirable, there could be a buffer or a barrier as a separation (Rempel et al., 2014). A barrier is a physical separation like a crash barrier, a buffer could be a small lane of grass in the middle or just road marking as a separation. The benefits to include a barrier are already shortly mentioned in section 4.2. To prevent collision of automated traffic with other traffic and the safety feeling of being physically separated from the slower moving traffic driving on the other lanes.

An example of a separated lane that is separated with a buffer-separation instead of a barrier separation is the truck lane. In this case the separation is operationally instead of physically by means of continuous lane markings. The benefit of this separation in comparison to physical separation is that it is relatively inexpensive, fast to implement and it is easy to remove if necessary (HNTB Corporation & Smith, 2010).

Van Loon, (2017), Senior Advisor Road Design at the Dutch Road Authority emphasizes the downsides of barriers as a separation between the dedicated- and regular lanes. Despite the fact that a barrier would prevent collision of AVs with un-automated traffic, a barrier is an extra obstacle near the road which increases the impact if a collision occurs. Furthermore, if the current standards for traffic safety should be maintained, a barrier in between the lanes would occupy extra space on the road which would be unnecessary. The width a barrier would need in the cross section of a highway would be minimal 3.5 meters, taking into account safety margin and width of the separation itself. Van Loon, (2017) also emphasizes the possibility of separated lanes by means of buffers in the form of lane marking. Another argument in favor of a buffer as separation instead of a barrier is the position the Dutch Road Authority takes in the network-operation-vision[2] (Rijkswaterstaat, 2017c). It is the ambition of the Dutch Road Authority to make the infrastructure future-proof, flexible and adaptive, also taking into account automated vehicles (Rutte et al., 2017). Developing a barrier in between the lanes makes the infrastructure more inflexible.

The importance of road marking and signaling, or more specific creating awareness among other road users of the existence of the dedicated lane, is crucial. Especially when there is no physical barrier between the lanes and undesired merging is possible. There is the possibility to use signage to increase the awareness of road users. Signage is a static signaling which is intermittent observed. Lane markings, on the contrary, are longitudinal signs that could be observed continuously.

4.4 Advantages and disadvantages of the road designs

Four final road design scenarios have been defined that will be further investigated in this research. The four scenarios are a Baseline Scenario (BL), the Continuous Access Lane (CAL), the Limited Access Lane with buffer (LAL) and the Limited Access Barrier Lane (LABL). The layouts of these scenarios are showed in Figure 4-6 to Figure 4-9.

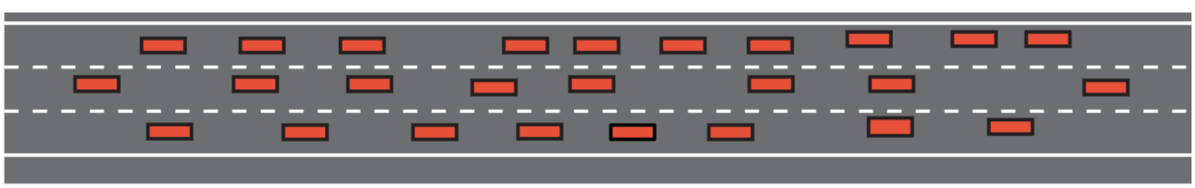


Figure 4-6. Baseline situation Driving Simulator (BL)

[2] Netwerkbeheersvisie

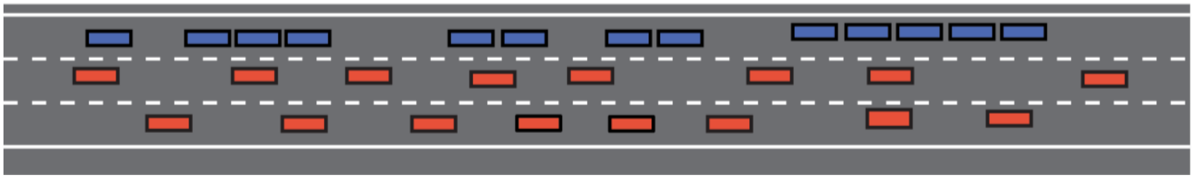


Figure 4-7. Separated continuous access lane (CAL)

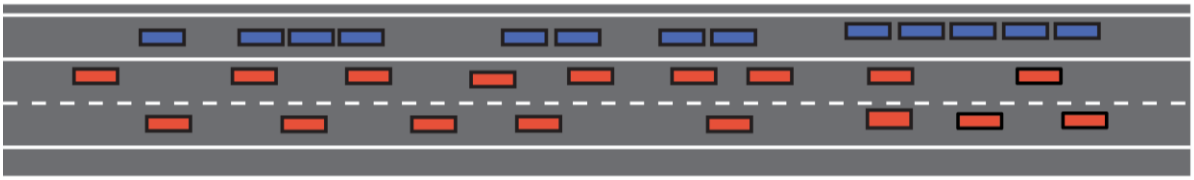


Figure 4-8. Separated limited access lane with buffer (LAL)

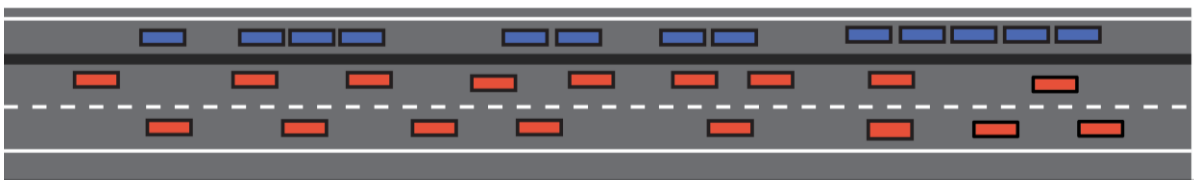


Figure 4-9. Separated limited access barrier lane (LABL)

The different proposed scenarios all have their advantages and disadvantages. The following table gives a summary of these advantages and disadvantages. The different (dis)advantages of the scenarios are based on criteria that should be taken into account for the road design, safety, costs, flexibility, efficiency, and durability, which are the most important criteria for the Dutch Road Authority. These criteria are based on the network-operation-vision and standards of the Dutch Road Authority.

Table 4-1. Advantages and Disadvantages of the different road design scenarios

	Advantage	**Disadvantage**
Continuous access lane	Low implementation costs Flexibility and adaptability of the infrastructure Continuous possibility to merge An automated vehicle with a system failure has the possibility to exit the lane Flexible use of lane during the day	Possibility of MVs wrongly merging in lane Possibility of collision Maneuvers all over the length of the lane

Limited access lane, buffer separation	Low implementation costs Flexibility and adaptability of the infrastructure Flexible use of lane during the day Possibility to check feasibility of the vehicle before entering the lane	Possibility of collision Maneuvers located on specific merging areas which might result in bottlenecks The inability of abruptly taking the highway exit
Limited access lane, barrier separation	Possibility of collision with vehicles in nearby lanes is eliminated Possibility to check feasibility of the vehicle before entering the lane	High implementation costs No flexibility and adaptability Maneuvers located on specific merging areas which might result in bottlenecks The inability of abruptly taking the highway exit Possibility to collisions with the barrier

4.5 Conclusion and discussion

In this chapter, the literature regarding the design of the dedicated lane was discussed. Based on this discussion it became clear that the most suitable position of a dedicated lane for AVs would be on the most left side of the road (left-hand traffic). Different separation methods have been discussed and the corresponding costs and benefits. Four final road design scenarios, that can be seen in in Figure 4-6 to Figure 4-9, have been defined that will be further investigated in this research. The four scenarios are a Baseline Scenario (BL), this is the current state of the road, three lane road without any dedicated lane, the Continuous Access Lane (CAL), a lane where AVs can merge in or out of the lane whenever it is the most suitable, Limited Access Lane with buffer (LAL), a separated dedicated lane that is separated with a continuous line, and the Limited Access Barrier Lane (LABL), a separated dedicated lane that is separated with a guardrail. The main benefit of a guardrail separation is taking away the risk of collision between the lanes. However, this is highly inefficient for the flexibility and adaptability of the highway system. Therefore, more research is necessary to provide more insights for better decision making.

5.0 Driving simulator experiment

This chapter outlines the methodology that is used to fill the knowledge gap that was identified in section 3.1 regarding the changing driving behavior of other road users. The process of the driving simulator experiment and the experimental design are elaborated on in section 5.1 and 5.2. The data collection and a descriptive analysis of this data is discussed in section 5.3. The methodology that is used is described in section 5.4 and the results of this experiment and the corresponding statistical tests are explained in section 5.5. Finally, section 5.6 summarizes the results and concludes this driving simulator experiment.

5.1 The driving simulator

AVs are still in development and do not yet publicly operate on the road. Therefore, it is impossible to conduct such experiment in the field. A driving simulator experiment is a suitable solution in terms of time, costs, safety for the participants, high internal validity, and consistent availability of performance data. It can test how the designed road scenarios are perceived and will influence their driving behaviors (Lee et al., 2011; Vienne et al., 2014). Moreover, the method can manipulate the scenario context easily and obtain a perfect balance of external factors (e.g. the behavior of the leading vehicle, the exposure time of the AVs or the composition of the platoons).

The driving simulator used in this experiment is a fixed-base, medium-fidelity driving simulator manufactured by GreenDino. This simulator is located at the Department of Transport and Planning, at the faculty of Civil Engineering and Geosciences, at Delft University of Technology. The simulator consisted of a dashboard mock-up with three high resolution screens (both side windows and the windshield), providing approximately 180-degree vision, Fanatec steering wheel, pedals and a blinker control. A picture of a participant driving in the driving simulator can be seen at Figure 5-1.

Figure 5-1. Driving simulator hardware

5.2 Experimental design and procedure

In order to conduct this experiment, four different scenarios were developed for the driving simulator as discussed in section 4.4. All four scenarios are identical in their environment (e.g. buildings, trees and landscape), the only aspect that is changed within the scenarios is the design of the infrastructure. Four infrastructure models were developed using Sketchup Pro, based on the Dutch road design standards, Richtlijn Ontwerp Autosnelwegen 2014 (Rijkswaterstaat, 2014)(e.g. radius of a curve, lane width, road marking). The roads were developed using Sketchup Pro and then exported as FBX files which could be imported in Unity. Unity is a game development software that is used to develop the environment for the driving simulator. The other elements in the surrounding of the scenarios (e.g. trees, buildings and hills) consists of the Standard Assets of the GreenDino Driving Simulator Package. For these surroundings a typical Dutch landscape was chosen, a flat open area, filled with a limited amount of trees, some scattered buildings with limited distractions alongside the road. Screenshots of the four scenarios developed in Unity can be found in Appendix A**.**

The asset package was also used to develop the RoadNet in the models. The RoadNet is the path where the vehicles in the simulation are able to drive on. Unfortunately, this asset package has some limitations. To obtain precise measurements in the simulator the distance to the center of the scenario should be kept limited. Therefore, the scenarios were developed as a straight road of approximately 3.5 km which is repeated over and over again. Whenever the player reaches the barrier of 3.5 km from the zero-point of the model, all the vehicles will be placed back 3.5 km in relation to the player. Hence, the player does not notice that it is being placed back repeatedly and it seems like it is driving over a continuous straight road. In order to overcome that the player notices it is driving the same stretch of road repeatedly different attributes in the environment are turned 'off' and 'on' whenever a player is passing a trigger. Another limitation of the Standard Asset Package is that the RoadNet should be limited in size to keep the scenario working properly and smoothly. Because of this, it was unfortunately not possible to let other vehicles drive on the utter right side of the road. A benefit of this is that the participants were not exposed to vehicles with a larger THW and were solely exposed to a smaller THW nevertheless, driving on the middle of the road with an empty lane on the right might also conflict with people's frame of reference. In order to overcome this conflict in the frame of reference the utter right lane was closed using Variable Message Signs (VMS) [3] above the road. The baseline scenario consisted of a road without any other vehicles besides the leading vehicle. This drive was used to measure drivers' base line THW without any influence of the platoons. In the other three scenarios the participants were slowly been taken over by the platoons since the platoons are driving one kilometer per hour faster than the leading vehicle.

On beforehand of this experiment a pilot experiment was conducted with five participants, recruited from my personal network, with the intention of gathering insights on the limitations and possible improvements of the experiment. These participants participated voluntarily and filled in an informed consent (Appendix D) before they started the experiment. This pilot study was conducted with approval

[3] Dynamisch route-informatiepaneel (DRIP)

of the TU Delft ethical committee. These participants expressed their opinions about the driving simulator, the four scenarios and the experiment set-up. Furthermore, the output data of this pilot experiment was analyzed to give an insight into the data processing process and the pilot made the researcher familiar with the steps that need to be taken to conduct the full experiment. Based on the findings from the pilot study minor adjustments to the driving simulator models and research set-up were conducted.

At first, participants were recruited by creating awareness at the faculty of Civil Engineering and Geosciences, the Faculty of Technology, Policy and Management and the Faculty of Architecture and the Built Environment at Delft University of Technology. Posters were distributed with a link were participants could subscribe for a suitable timeslot. In total 35 participants were recruited for this experiment. Due to time and resource limitations it was assumed that 35 participants will provide enough insights to draw reasonable conclusions. To exclude causal explanations based on sociodemographic differences only drivers between 20 and 30 years old, and all of them have a valid driving license with at least two years of driving experience on the Dutch highway system were able to subscribe for the experiment. The procedure of this experiment was approved by the Human Research Ethics Committee of Delft University of Technology.

Before they conducted the experiment, they filled in a questionnaire concerning their socio-demographic characteristics and their attitudes towards technology, automated vehicles and their willingness to drive an automated vehicle. The participants also signed an informed consent declaring that they are participating voluntarily and are aware of the possible risks of simulator sickness. They were also informed that the experiment was about automated vehicles but were not informed about the measurement of the THW.

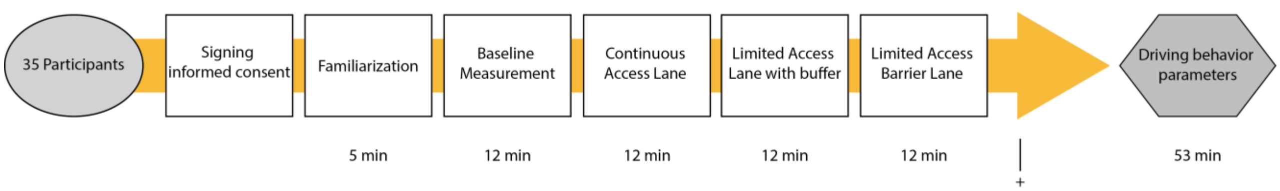


Figure 5-2. Driving simulator experiment scheme

The participants were instructed at the start of the experiment to follow the red car that drove in front of them. This was the leading vehicle from which their THW was measured. The participants were asked to drive 5 minutes in an environment unrelated to the experiment to get familiar with the driving simulator and to get rid of the fun factor that could be involved in a driving simulator experiment (Crundall, Andrews, Van Loon, & Chapman, 2010; Lee & Kim, 2009). The design of the experiment was composed of four drives of 12 minutes: the three road design scenarios as explained before and a baseline measurement scenario. An exposure time of 12 minutes was chosen for this experiment based on the literature that suggested that a shorter exposure time is not sufficient to get a distance adaptation (Gouy, 2013) and is also in line with similar driving simulator studies (Daun et al., 2013; Hoedemaeker & Brookhuis, 1998; Varotto, Hoogendoorn, van Arem, & Hoogendoorn, 2015). The order in which they drove these scenarios was balanced between participants to overcome the influence of the order effect. In every conducted drive the first minute of the data was deleted because it takes drivers some time to reach the headway they desire and accelerate to a desirable speed. Between each two drives, there was a short resting break of a few minutes depending on the participants needs. In total, the experiment took more or less an hour to complete all the scenarios. A scheme of the experiment and the corresponding time it took for each drive is shown in Figure 5-2. During the entire experiment it was regularly checked if the participants experienced any discomfort.

After the driving simulator experiment, a post experiment questionnaire was filled in by the participants. In this questionnaire it was also measured if the participants experienced any discomfort during the experiment. After the questionnaire was filled in by the participants they received their monetary compensation and signed a form that they received this compensation.

The entire process of the driving simulator experiment including all the steps that were necessary to conduct the experiment can be found in Figure 5-3.

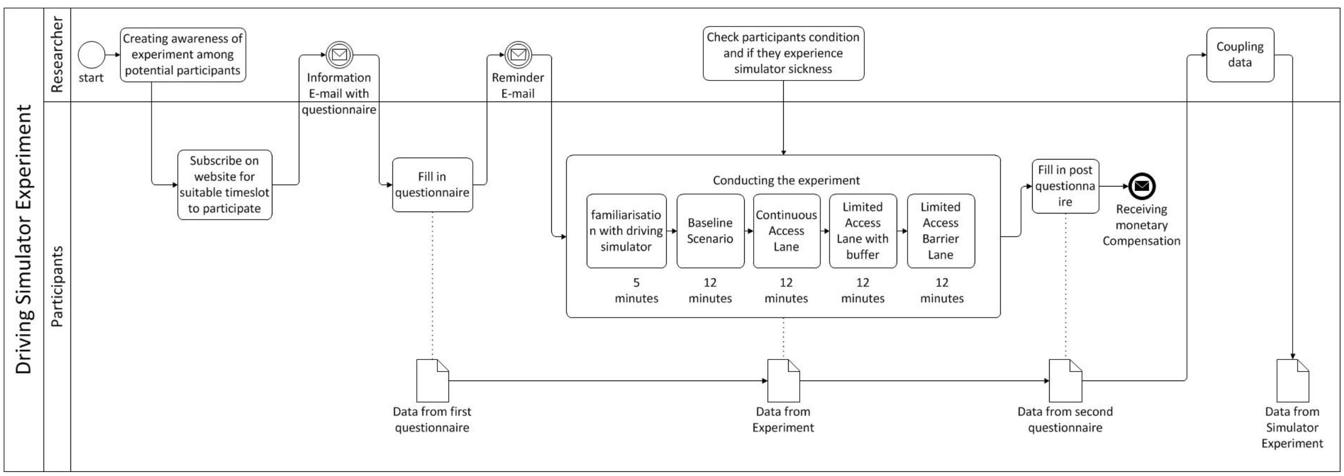


Figure 5-3. Process of Driving Simulator Experiment

5.3 Data collection and descriptive analysis

This section provides an overview on how the data was collected, which data was collected and a thorough visual inspection of the collected data. The types of data that were collected during the process can also be seen in Figure 5-3, where it is shown in the bottom line represented by a data element. This section gives already the first insights in the results observed in the driving simulator experiment.

5.3.1 Data collection

The first data that was collected was collected using a questionnaire. This post experiment questionnaire collected sociodemographic data (e.g. gender, year of birth, nationality) as well as their attitude towards technological developments and automated vehicles, as can be seen in Table 5-1. Their attitudes towards these aspects were rated on a Likert scale, which is the most widely used to measure attitudes (Mc Leod, 2008). This questionnaire can be found in Appendix B. The questionnaire was developed in Google Forms, an online questionnaire development tool. This made it possible to directly export the data in a Comma Separated Value (CSV) format which could be used for data analysis.

The data that was collected from the driving simulator was recorded at a frequency of 10 Hz. A script of the driving simulator scenario and the logged data of the subject vehicle (the participant who is driving), the Leading Vehicle and all vehicles within a distance of 10 meter were saved. The data and the corresponding variables that were collected in the driving simulator are listed in Table 5-1. The data from the driving simulator is logged in the JavaScript Object Notation (JSON) format. This format is not suitable for data analysis and is therefore converted by an online tool to CSV format. This format was opened in Microsoft Office Excel to further process the data into the variables that were necessary for the statistical analysis.

The time headway was calculated using the basic traffic flow formula [3] (Knoop, 2014):

$$h_i = \frac{s_i}{v_i} \qquad [\ 3\ ]$$

Where h_i is the time headway, s_i the space headway between the subject vehicle and the LV and v_i the velocity of the subject vehicle.

After the driving simulator experiment, a post experiment questionnaire was filled in by the participants. In this questionnaire (also in Appendix B) the participants were asked again about their attitudes towards technology, automated vehicles and their willingness to drive an automated vehicle and there preference regarding the different road designs they drove on. The reason for this second questionnaire was to test whether their attitude towards AVs was changed after experiencing it and to obtain some insights in their perceptions of the dedicated lane. This questionnaire was also developed in Google forms.

Table 5-1. Data that is collected in this research

Instrument to collect data	**Collected from**	**Variables**
Prequestionnaire	Participant	Gender; year of birth; number of years of driving experience; possession of car; nationality; attitude toward technological developments; attitude towards automated vehicles;
Postquestionnaire	Participant	Driving simulator experience; attitude toward technological developments; attitude towards automated vehicles;
Driving simulator	Participant as the subject vehicle	Timestamp; Position(X,Y,Z); Heading(X,Y,Z); Velocity(X,Y,Z); Acceleration(X,Y,Z)
Driving simulator	Leading Vehicle and Vehicles within 10 meter	Name; Distance to player; Position(X,Y,Z); Heading(X,Y,Z); Velocity(X,Y,Z); Acceleration(X,Y,Z)

The data collected in the driving simulator was combined with the data collected in the pre- and post-questionnaires to get one comprehensive dataset. This data was converted to a longbook dataset to make it possible to conduct the desired statistcal tests, an explanation of these tests is provided in section 5.4.

5.3.2 Descriptive analysis

This section contains visual representations and inspection of experimental data. When the individual time headway as a function of the time stamp is inspected, it becomes clear that there is one driver that deviated markedly from the average behavior of the sample of drivers. As can be seen in Figure 5-4, participant number 3 adopts extraordinary high values for its THW. Since it appeared that the model-fit increases in the statistical tests, elaborated in the following section, when this participant is excluded from the data, this participant is excluded from the data set. The model fit is used to consider which model 'fits' the data best (The University of Kansas, 2006).

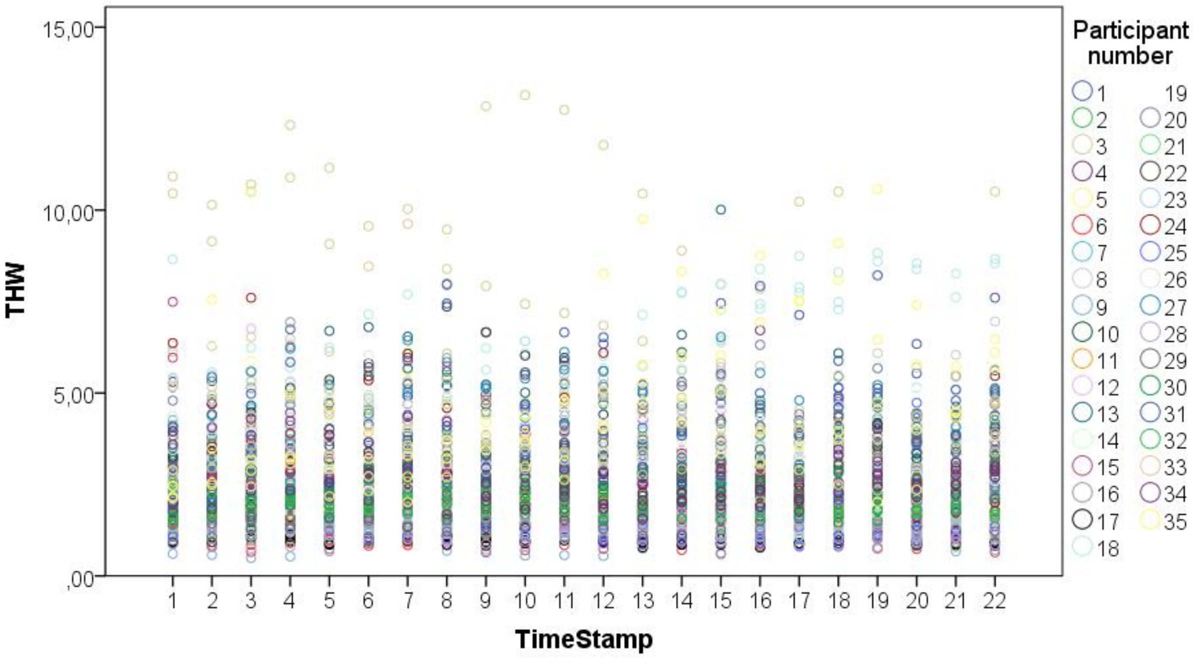


Figure 5-4. Average THW per scenarios per participant

With the exclusion of participant 3, took 34 Participants of Dutch Nationality part in this experiment. Of these 34 participants 13 were female and 21 were male and they all had a valid driving license in the Netherlands and at least two years of driving experience on the Dutch highway system. The age of the participants ranged between 20 and 30 years (M = 23.9 years, Std. = 2.2 years) and the driving experience ranged between 2 and 10 years (M = 5.1 years, Std. = 1.5 years). Of the 34 participants merely 3 participants already drove in a driving simulator before, they had a slightly smaller THW (M = 2.6s) in comparison with the average (M = 3.0s) but because of the small amount of people this is not expected to be influential on the results.

Furthermore, the participants had a very positive attitude towards technology and the influence of technology on society, as can be seen in Figure 5-5. This technology-oriented sample could be explained by the fact that participants were recruited at Delft University of Technology.

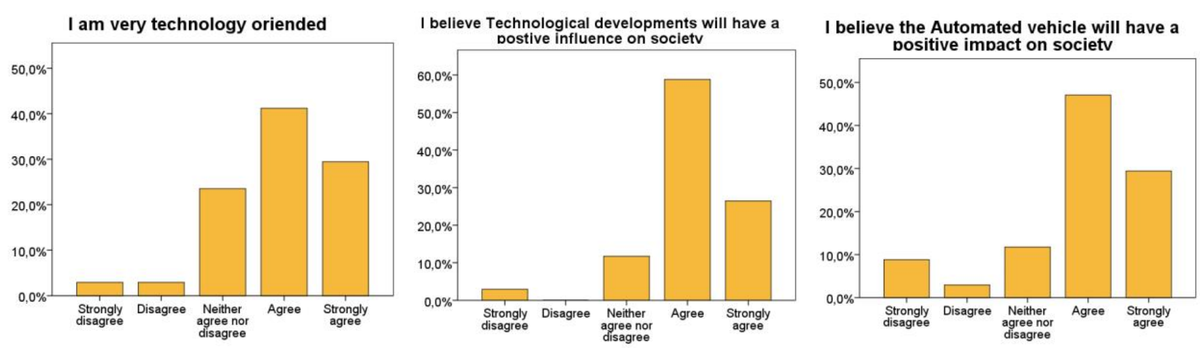


Figure 5-5. Technology orientation graphs

According to the literature, as indicated in section 2.5 the socio-demographic factors that possibly could influence the THW are gender, age and the number of years of driving experience. When these variables were subjected to visual inspection some patterns could be identified.

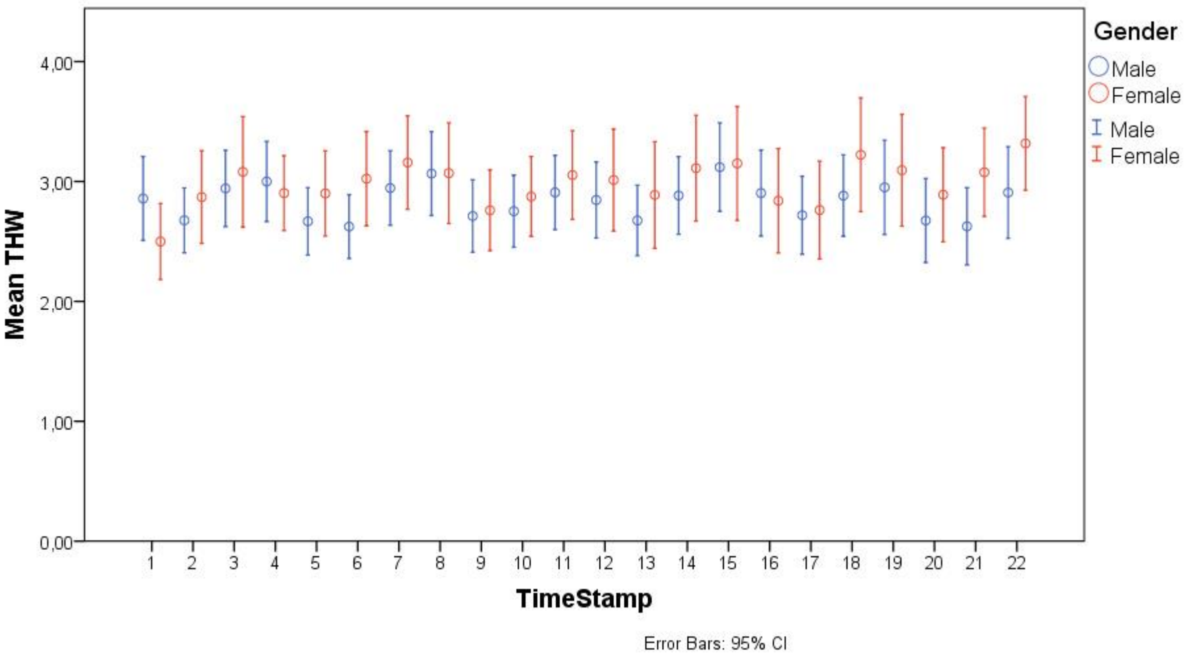


Figure 5-6. Mean THW based on gender averaged over the four different scenarios

As can be seen in Figure 5-6 the average THW of males is distinctly lower in comparison of the average THW of females. It can also be noticed that the standard deviation of the THW for females is bigger compared to that of males. This could be because of the differences in the sample sizes. This pattern is in line with the investigated literature where males express themselves in riskier driving behavior and prefer a closer gap than females (Bener & Crundall, 2008). An independent T-test was also conducted to test if gender had an influence on the THW participants kept in the driving simulator and the differences between male and female appeared to be significant t = -2.643, p = 0.008.

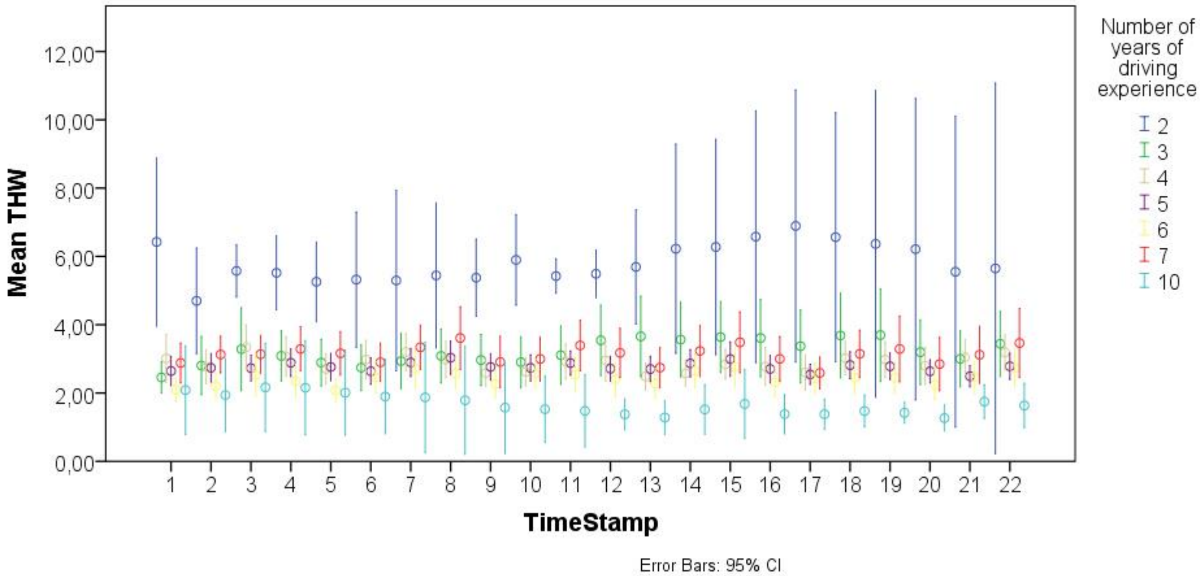


Figure 5-7. Mean THW based on number of years of driving experience over the different scenarios

Further, the years of driving experience and the THW is investigated. It can be seen from Figure 22, there is a relation between the average THW and the number of years of driving experience, the less years of driving experience, the higher the THW. Nevertheless, 2 years and 10 years of driving experience are both only represented by one participant in this dataset and therefore it would also be possible that this pattern is based on coincidence.

A Pearson correlation analysis was conducted to examine whether there is a relationship between THW and the number of years of driving experience. The results revealed a significant and negative relationship ($r = -.234$, $p < 0.005$). This would imply that when the number of years of driving experience increases the THW decreases which is in line with the expected results in Figure 5-7. Nevertheless, this observed relationship is not in line with the literature, which indicated that there is no relationship between the number of years of driving experience and the THW.

Also, when the years of driving experience is divided into a categorical variable as can be seen in table X, there is a statistically significant difference between groups as determined by one-way ANOVA ($F = 93.717$, $p < 0.05$).

Table 5-2. Years of driving experience in groups

Years of driving experience groups	Mean	Std.	% of Total N
2-3 years of driving experience	3,73	2,04	15,0%
4-5 years of driving experience	2,81	1,26	50,2%
6 years or more of driving experience	2,65	1,31	34,8%
Total	2,89	1,47	100,0%

The other socio demographic factor is age. This variable is also related with the number of years of driving experience (which is quite logical) as became clear when this relationship was tested with a simple linear regression ($F = 2418{,}963$, $p < 0.005$). Nevertheless, a clear difference of THW within the different ages does not seem too visible as can be seen in Figure 5-8. Although in the literature age is clearly mentioned as a variable that would influence driving behavior, it does not seem to be the case in this dataset. An explanation could be provided by the fact that when age is investigated it is conducted over a sample with multiple age categories. In this case all the participants are within the age of 20-30 which would normally be grouped as one age category. Therefore, it seems to be that driving experience is a more important indicator in the prediction of the THW than age in this study.

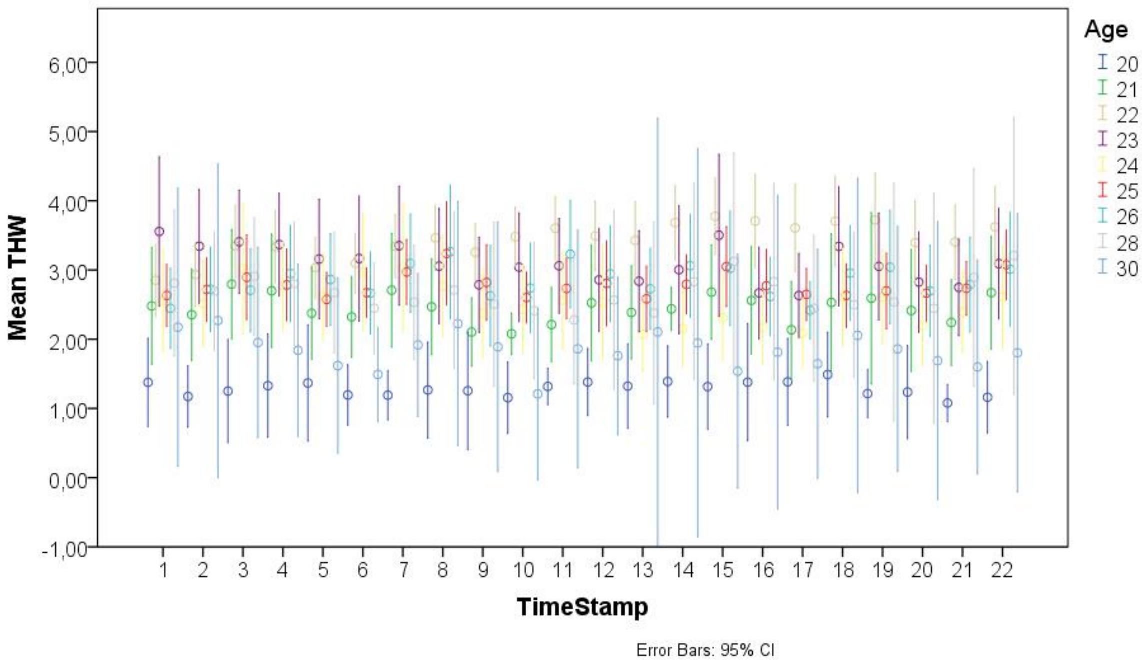


Figure 5-8. Mean THW based on age averaged over the four different scenarios

Thus, it can be concluded that number of years of driving experience and gender are the sociodemographic variables that have significant influence on the THW and therefore should be included in the rest of this research.

Obviously, it should also be inspected if the road design scenarios influence the THW. The THW was measured with a frequency of 10 Hz for every scenario. When the data is subjected to a visual inspection it becomes clear that there is a difference in the average THW regarding the four scenarios (BL, LABL, CAL and LAL) as shown in Figure 5-9.

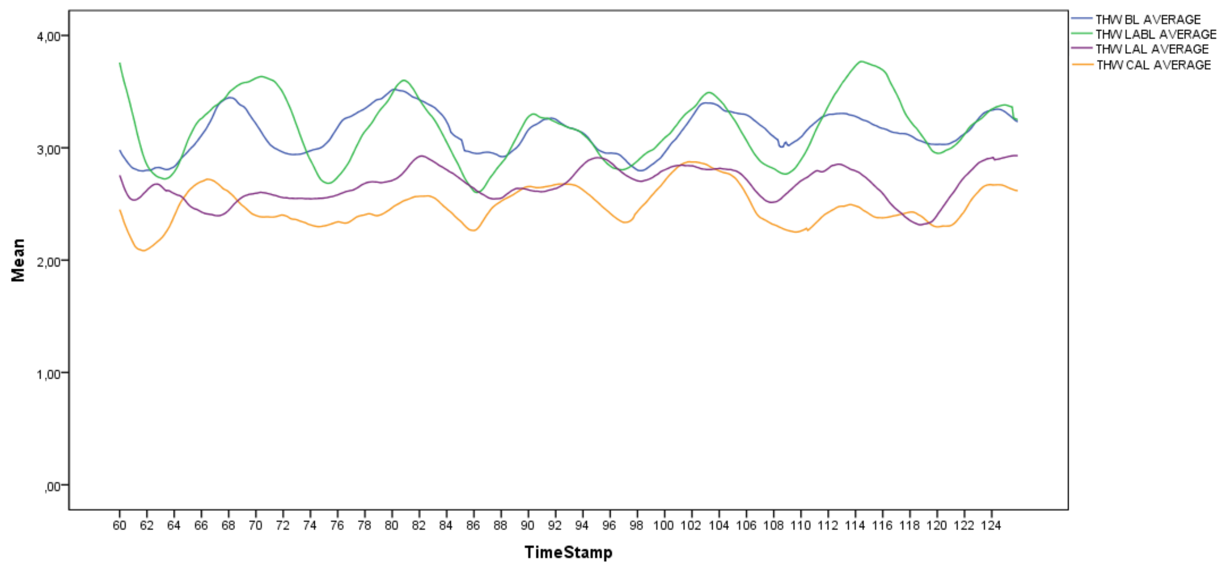


Figure 5-9. Average THW over time per scenario

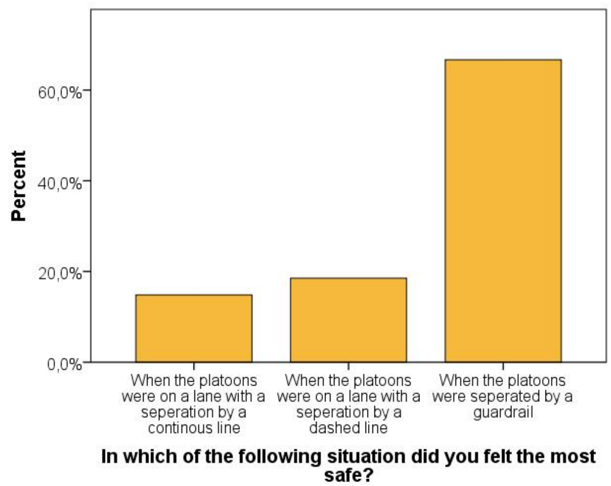
As can be seen the average THW for the LAL and the CAL scenarios are lower than the Baseline scenario and the LABL scenario. The difference between the scenarios expressed in the average headway of all the measured values per scenario can also be seen in Table 5-3.

Table 5-3. Average THW per scenario

Scenario	**Average THW(s)**	**Std. THW (s)**
Baseline Scenario (BL)	3,2407 s	1,55736 s
Limited Access Barrier Lane (LABL)	3,1710 s	1,56652 s
Limited Access Lane with buffer (LAL)	2,6974 s	1,33258 s
Continuous Access Lane (CAL)	2,4793 s	1,26117 s

So far, the visual inspection seems to have promising results. Additional investigations whether these differences within the scenarios are also statistically significant will be elaborated on in section 5.5.

Furthermore, the data from the post experiment questionnaire gave also some interesting insights. These questions mostly focused on a repetition of the question about their attitude toward technology and automated vehicles and about their experiences of the four different scenarios. their attitude towards technological developments and AVs didn't change significantly, but their experiences gave some interesting insights.



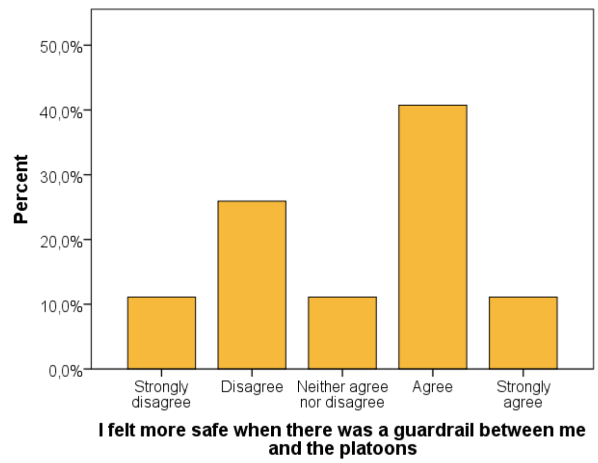


Figure 5-10. Road scenario that felt the most safe

Figure 5-11. Felt more safe with a guardrail separation

When it was asked in which road design scenario they felt the most safe, 66.7% of the participants said they felt the most safe when they were separated by a guardrail as can be seen in Figure 5-10. This was also confirmed with the question if they felt more safe when they were separated by a guardrail where 40.7% agreed and 11.1% strongly agreed (Figure 5-11).

Although more than 50% of the participants strongly disagreed with the statement that they felt unsafe on a certain moment during the driving simulator experiment, 14.2% has indicated in writing that they felt unsafe when the guardrail was not besides them when a platoon was driving next to them. The participants indicated also that they felt unsafe when the platoon was taking over directly next to them on the left, which is the 'normal' side for vehicles to take over in the Netherlands, when there wasn't a barrier or buffer in between them. The literal statements they made in Dutch are attached at appendix H. Also, when the participants were asked at which situation they felt the more safe 66.7% answered the situation with the guardrail as can be seen in Figure 5-10. Because of the small sample of 35 participants, these are only 5 participants who implied this unsafety perception and therefore this might be an interesting cornerstone for further research.

5.4 Methodology

To analyze the data multiple methods were found to be applicable. To determine that there indeed is a statistical difference between the four scenarios a repeated measures ANOVA was found to be suitable. In many similar driving simulator studies (Brookhuis, van Driel, Hof, van Arem, & Hoedemaeker, 2009; Risto & Martens, 2014) a repeated measures ANOVA was used for statistical analysis.

A repeated measures ANOVA is a test to detect any overall differences between related, not independent, means. It tests for whether there are statistical differences between different conditions. The null hypothesis of this test [4] is therefore that there are no significant statistical differences and all means are equal. Where μ is the mean of the population and k the number of related groups, in this case the different scenarios that were tested.

$$H_0: \mu_1 = \mu_2 = \mu_k \qquad [4]$$

This research design can be used to test differences in mean scores under three or more different conditions. A benefit of this statistical test is that it is possible to make multiple measurements of the same participant rather than measuring different participants for the different conditions/scenarios. A benefit is that repeated measures designs can have more statistical power because of the control of errors that might occur from the variance between participants. This is what makes it different from a regular independent ANOVA. Where in an independent ANOVA within-group variability is equal to the error variability, a repeated measures ANOVA can further decrease this error term by extracting the variability due to individual differences between participants (Gribble, 2016). This makes it possible to conduct solid research with a limited amount of participants and achieve the same statistical power, which is in the case of a time consuming driving simulator experiment extraordinary beneficial (Frost, 2015). A challenge regarding repeated measures designs is the order effect. This implies that the result could be influenced by the order in which the participant is measured. In this experimental design the order of the scenarios was balanced between participants to overcome the influence of this order effect, the order in which the participants took the experiment can be found in Appendix 0. In order to conduct a repeated measures ANOVA, the assumption of sphericity should be tested to see if it has been violated. Sphericity is obtained when the variances of the differences between all combinations are equal. It is important to test whether this assumption is violated because a violation can cause the test to become too liberal. To test if this has been violated Mauchly's Test of Sphericity should be conducted. It assumes a null hypothesis that the variances of the differences are equal, thus if the test is significant the null hypotheses can be rejected and the assumption of sphericity is violated.

The logic behind a repeated measures ANOVA is the following, an F-statistic is calculated as the ratio of the mean sum of squares over the different conditions ($MS_{conditions}$) to the mean sum of squares of the error variability (MS_{error}). This is also an advantage of the repeated measures ANOVA over the independent ANOVA because it can further ramify this error term, reducing its size.

$$F = \frac{MS_{conditions}}{MS_{error}} \qquad [5]$$

In order to calculate mean sum of squares the conditions variability ($SS_{conditions}$) and the error variability (SS_{error}) have to be calculated using the following formulas. Where k is the degrees of freedom and n the number of subjects.

$$MS_{conditions} = \frac{SS_{conditions}}{(k-1)} \qquad [6]$$

$$MS_{error} = \frac{SS_{error}}{(n-1)(k-1)} \qquad [7]$$

By using these basic formulas statistical software calculates the F-statistic which indicates if the differences are statistically significant. Therefore, a repeated measures ANOVA is the most suitable research method to test if there is a significant difference within the different scenarios.

When there is determined whether or not there is a significant difference between the four scenarios another statistical test to investigate the weight and direction of the parameters that exercise influence on the THW is desirable. The research design that could be used for this purpose is the Linear Mixed-Effect model.

A difference is that with the ANOVA we analyzed the mean values of the different scenario, in the Mixed-Effect Model we analyze the data per time unit, and analyzing data where the type of outcome is continuous is the most advanced body of research (Verbeke & Molenberghs, 1997). Linear Mixed-Effects Models are statistical models for continuous outcome variables in which the residuals are normally distributed but may not be independent or have constant variance (West, Welch, & Galecki, 2007). They are quite often used with repeated measures data. When measurements are made on the same participant over time they are likely to be correlated, and the linear mixed model can account for this. This model involves the estimation of covariance parameters to capture this correlation. In this model factors and covariates are assumed to have a linear relationship to the dependent variable, the factors are the categorical predictors (e.g. Gender) and the covariates are the scale predictors (e.g. number of years of driving experience). Within the categorical predictors, each level of a certain factor can have a different effect on the dependent variable relative to the reference level, while the covariates are assumed to be linearly correlated with the dependent variable (Nguyen, Sentürk, & Carroll, 2008).

Furthermore, this model distinguishes between fixed-effect factors and random-effect factors. The fixed effects are variables whose values are all represented in the dataset and is defined as a categorical or classification variable for which all levels of interest are included. While random effects can be seen as a random sample from a larger population of values, where not all random factors are present in the data. This random effect helps to explain the variability of the dependent variable. To include a random effect to make the model fit better a random factor is entered the model as random intercept, representing random deviations for a given subject from the overall fixed effects (West et al., 2007).

A benefit of the Linear Mixed Model is that it models individual differences by assuming random intercepts for each participant. This means that the model calculates a random intercept value for every participant. In the case of this research this would be very suitable because every individual has a slightly difference in the preferred distance they keep, thus THW.

Therefore, the basic structure of the Mixed model is the following:

$$Y_{ti} = \beta_1 * {X_{ti}}^1 + \beta_n * {X_{ti}}^n + \gamma_{ni} * {Z_{ti}}^n + \varepsilon_{ti} \qquad [\,8\,]$$

Where Y_{ti} is the continuous response of i-th subject of cluster t. The assumption is that there are two sets of variables, fixed and random variables. Here β is associated with the fixed effects and γ is associated with the random effects for variables X and Z, respectively. Therefore each β represents a fixed effect of a one-unit change in the corresponding X variable on the mean value of the dependent variable Y_{ti}, assuming all other variables remain fixed. Furthermore the random effects γ represent the random of the model over the Z variables and ε_{ti} represents the residual (West et al., 2007). This makes it possible to predict the outcome for a specific person over the observed values.

This research design is very suitable because it makes it possible to measure the influence of multiple effect at the same time. Another benefit of this model is clement with missing values and does not affect the outcome or reliability of the outcome (Howell, 2010).

5.5 Results

The data is subjected to visual inspection and a descriptive analysis is provided in section 5.3. This section provides results of statistical tests, based on the methods explained in the previous section.

5.5.1 Results of the Repeated Measures ANOVA

In the descripted analysis it appeared that there were differences between the THW the participants took in the four developed scenarios. To test whether this observed difference is statically significant ($p< 0.05$) a repeated measures ANVOA was conducted. For this data set Mauchly's Test of Sphericity indicated that the assumption of sphericity has been violated, $X^2(2) = 683.109$, $p <.0005$, therefore a Greenhouse-Geisser correction was applied on the ANOVA to generate a more critical F-value.

A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean THW differed statistically significantly between the four different scenarios ($F(2.014, 6193.535) = 1089.296, p< 0.05$). Post hoc tests using the Bonferroni correction (Laerd Statistics, n.d.) revealed that the differences between every scenario was statistically significant ($p<0.05$). The results are presented in Table 5-4. Results of Repeated measures ANOVA. The differences in mean values with respect to the baseline measurement were 0.156(LABL), 0.900(CAL) and 0.766(LAL). Therefore it can be concluded that differences between the four scenarios are statistically significant in terms of the average THW.

Table 5-4. Results of Repeated measures ANOVA

Source		**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Scenarios	Greenhouse-Geisser	1819,478	2,014	903,638	1089,296	0,000	0,262
Error(Scenarios)	Greenhouse-Geisser	5137,917	6193,535	0,830			

5.5.2 Results of the Linear Mixed-Effect Model

After it was proven that the influence of the scenarios is statistically significant, the influence of the scenarios in combination with other socio-demographic factors should also be investigated. A mixed model analysis was used to test the influence of these factors on the THW. Because of the high frequency of the measured data, the data was transformed to a frequency of 0.03 Hz, which means that there are 22 time points in every scenario for every participant.

For this model, the model fit improves significantly (from a Log-likelihood = 10097.180 to a Log-likelihood = 8104.661) according to the likelihood ratio test statistics when the random intercept was included. Furthermore, it was also tested if the exclusion of participant 3 had any influence on the significance, this was not the case. The model-fit increased when this participant was excluded from the data (from a Log-likelihood = 9042.160 to a Log-likelihood = 8104.661).

The Linear Mixed Model was conducted with the participant number as subject and the THW as dependent variable. The covariance structure that is chosen for this model is the diagonal structure, which is the most common covariance structure for repeated effects and supported by literature (Williams & Lu, 2015). The results of the model are presented in Table 5-5.

Table 5-5. Estimates of Fixed Effects

						95% Confidence Interval	
Parameter	**Estimate**	**Std. Error**	**df**	**t**	**Sig.**	**Lower Bound**	**Upper Bound**
Intercept	3,795	0,649	31,022	5,848	0,000	2,472	5,119
[scenario=Baseline]	0,539	0,047	2333,481	11,529	0,000	0,448	0,631
[scenario=LABL]	0,421	0,047	2418,268	8,993	0,000	0,329	0,513
[scenario=CAL]	-0,204	0,044	1936,996	-4,621	0,000	-0,290	-0,117
[scenario=LAL]	0	0					
[Gender=Male]	-0,191	0,356	30,918	-0,536	0,596	-0,918	0,536
[Gender=Female]	0	0					
Number of years of driving experience	-0,199	0,112	30,919	-1,783	0,084	-0,427	0,029

a. Dependent Variable: THW.

As can be seen in Table 5-5 not all parameters are statistically significant, only the scenarios have a statistically significant influence on the THW. Nevertheless, according to the likelihood ratio test statistics, the model including the sociodemographic parameters (Log-likelihood = 8104.661) is superior to the model including solely the scenarios parameters (Log-likelihood = 10254.957) in terms of overall model fit. These parameters are not significant, this could be explained by the fact that the sample group of 34 participants is not large enough to have a statistically significant result of the socio-demographic variables. The socio-demographic factors that decrease the log-likelihood are gender and years of driving experience. When the age of the participants is added to the model, the model fit decreases. When we inspect the Parameter estimate values they are consistent with the expectations for these values. When someone is male the THW decreases and with an increase of the years of driving experience the THW decreases as well.

As elaborated in section **Fout! Verwijzingsbron niet gevonden.** the basic structure of the Mixed model is the following:

$$Y_{ti} = \beta_o + \beta_1 * X_{ti}{}^1 + \beta_n * X_{ti}{}^n + \gamma_{ni} * Z_{ti}{}^n + \varepsilon_{ti} \qquad [9]$$

For this model it would imply:

$$THW_{ti} = \beta_0 + \beta_1 * Baseline_{ti}{}^1 + \beta_2 * LABL_{ti}{}^1 + \beta_3 * CAL_{ti}{}^1 + \beta_4 * Gender_{ti}{}^1 + \beta_5 * Driving\ experience_{ti}{}^1 + \gamma_{ni} * Z_{ti}{}^n + \varepsilon_{ti}$$

Where β_0 is the fixed effect intercept, β_n the Fixed effect estimate values, γ the random effect intercept, Z_{ti} the random effect variable and ε_{ti} the residuals. Dummy coding was used for categorical variables

Table 5-6. Pairwise Comparisons

(I) scenario		**Mean Difference (I-J)**	**Std. Error**	**df**	**Sig.**	**95% Confidence Interval for Difference**	
						Lower Bound	**Upper Bound**
BL	LABL	0,092	0,070	2475,683	1,000	-0,093	0,278
	CAL	0,786	0,068	2510,821	0,000	0,607	0,966
	LAL	0,581	0,069	2580,509	0,000	0,399	0,762
LABL	BL	-0,092	0,070	2475,683	1,000	-0,278	0,093
	CAL	0,694	0,067	2527,877	0,000	0,516	0,871
	LAL	0,488	0,068	2607,096	0,000	0,308	0,668
LAL	BL	-0,581	0,069	2580,509	0,000	-0,762	-0,399
	LABL	-0,488	0,068	2607,096	0,000	-0,668	-0,308
	CAL	0,206	0,066	2234,048	0,011	0,032	0,379
CAL	BL	-0,786	0,068	2510,821	0,000	-0,966	-0,607
	LABL	-0,694	0,067	2527,877	0,000	-0,871	-0,516
	LAL	-0,206	0,066	2234,048	0,011	-0,379	-0,032

a. Dependent Variable: THW.

c. Adjustment for multiple comparisons: Bonferroni.

The parameter estimates values for the scenarios are consistent with the difference within the pairwise comparison. Another interesting result from the pairwise comparison conducted with a Bonferroni adjustment is the insignificance of the comparison of the baseline scenario with the LABL scenario. The p value is, as can be seen in Table 5-6, insignificant ($p > 0.05$). This insignificance would imply that people do not adapt their THW when there is a guardrail between them and the platoons. Nevertheless, based on earlier conducted results it is still assumed that there is a small (significant) difference between the Baseline and the LABL scenario.

5.6 Conclusion and discussion

Based on this driving simulator experiment it can be stated that there is an observed behavioral change in the driving behavior of drivers of manual vehicles when they are in the proximity of platoons of AVs. Moreover, it can also be concluded that the type of separation between these lanes has a significant influence on the behavioral changes of MVs in the proximity of platoons of AVs. Mean THW differences have been observed with regard to the baseline measurement and within the three road design scenarios. These differences in mean values were found to be significantly different. The socio demographic factors of gender and number of years of driving experience influence the THW of the drivers of manual vehicles as well. However, these variables were not found to be significant in the linear mixed model. The differences observed in the driving simulator experiment as can be seen in Table 5-3 are in line with earlier conducted research discussed in the literature review. Gouy, (2013) conducted a driving simulator experiment measuring the THW of manual vehicles in different platooning configurations and she found a mean value of 2.61s for the baseline measurement and a THW of 2.04s when platoons maintaining a time gap of 0.3s were driving next to the manual vehicles. Therefore, a similar decrease in THW is observed in the study by Gouy, (2013) as observed in this driving simulator experiment. These results confirm the research hypothesis that people will adapt their driving behavior when driving in proximity of a platoon on a dedicated lane by reducing their THW. The expectation was that the THW would be decreased when the drivers of the manual vehicles were directly next to the platoons and this effect on the frame of reference would be less when they were separated by a physical barrier such as a guardrail. This is completely in line with the observed THW measured in the driving simulator experiment. This decrease in THW when drivers are directly driving next to a platoon might conflict with the safety benefits. This is not investigated in this study and is therefore an aspect that should be further investigated.

Regarding the methodology that is used for the driving simulator experiment there are some aspects that could be improved but were not able within the time and resources available for this thesis. The limitations of the driving simulator were unexpected setbacks, but within the current research design it is reasonable to assume that these limitations didn't influence the results presented in this thesis. One of these limitations was absence of vehicles on the right side of the road. This limitation was solved by closing this lane using VMS. An improvement would be to let other vehicles (e.g. heavy goods vehicles) drive on the right side of the road to make it more realistic to drive on the middle lane. Moreover, there was a limitation of the length of the road. This limitation did not actually influence the methodology of the driving simulator experiment but might made the experiment less interesting for the subjects that participated in the experiment, which might have influenced the results. Measuring the THW on a completely straight road is more precise, but the lack of complex driving maneuvers might have bored the participants which might have caused a lack of attention. Nevertheless, based on the feedback obtained from the post experiment questionnaire this was not an issue. In this experiment 35 drivers participated, this is considered sufficient when compared to similar studies using driving simulators in the literature, nonetheless bigger sample of drivers with different sociodemographic characteristics would further validate the conclusions drawn from this experiment. Besides these limitations the driving simulator experiment seems to be very suitable methodology to obtain the desired results and get more insight in the behavioral adaption of drivers of manual vehicles.

Another aspect that should be elaborated upon is the carryover effect of other vehicles, the carryover effect of speed is a well-known phenomenon (Casey & Lund, 1992). This implies that drivers have a sensory response when they experience a change in relative motion (Matthews, 1978; Schmidt & Tiffin, 1969). In this case the change in relative motion might be caused by the appearance of other vehicles. Therefore, a reason behind the decreased THW in the scenarios with regard to the baseline measurement could also be caused by the carryover effect of speed by the other vehicles, that the participants were pulled with the other vehicles to maintain a shorter headway instead of because the actual short THW the platoons kept. A situation with regular cars keeping a large THW driving next to the participant wasn't measured in the driving simulator and including this measurement could be an improvement for further research. Nevertheless, even with the assumption that this effect might be the cause for a decreased THW, the decreased THW within the three road design scenarios, where they all were driving next to a platoon of AVs, is still not explained. Therefore, it is important to be aware of the existence of this effect but it is reasonable to assume that the decreased THW is a result of the appearance of platoons maintaining a shorter THW and not solely the carryover effect.

Furthermore, the behavioral adaptation that is measured in the driving simulator is measured over a limited time. It should be considered that this behavioral adaption is of a temporary nature. The introduction of automated systems may impact drivers' behavior, but the changes observed may develop as drivers first discover the system, learn all possibilities and limitations and become expert users. Therefore, to conclude if this behavioral change is permanent should be investigated when drivers are exposed to platoons of AVs for a longer period.

6.0 VISSIM Traffic modelling

This chapter is divided into three parts, section 6.1 explains the methodology that is used for the traffic flow modelling, section 6.2 presents the results from the different models that were developed, and section 6.3 discusses and concludes this section. The results from the driving simulator experiment are used as an input for the simulation to scale up the effect at the traffic flow level and assess the implications on the traffic flow capacity.

6.1 Methodology

As concluded in section 2.4.1 VISSIM is a suitable tool for investigating the impacts on traffic flow based on microscopic models. The road design structure of the four models that are developed in VISSIM (BL, LABL, CAL and LAL) can be found in Appendix E. Nevertheless, they are elaborated shortly in this section.

Baseline Scenario (BL): In this model the AVs as well as the MVs have the same driving behavior and maintain the same time headway (THW) for the baseline scenario. Therefore, technically there are no AVs in this scenario. All vehicles are allowed to drive on every lane and do not have a preference of lane choice. On this road section the 'slow lane rule' is applied which means that vehicles prefer driving on the right side of the road which is also the case in the Netherlands. At the end of the road, 20% of the vehicles will take the highway exit (off-ramp).

Limited Access Barrier Lane (LABL): In this model all the vehicles start on various lanes and the AVs have to change lanes to the most outer left lane to get on the dedicated lane for AVs. MVs are not allowed to enter this lane. After a dedicated lane of 1.3 km the AVs have the possibility to exit the AV lane on a weaving section with a length of approximately 600 meters (Goemans, Daamen, & Heikoop, 2011)("Richtlijn Ontwerp Autosnelwegen 2017," 2017) to take the highway exit that is coming up. At this road design the 'slow lane rule' is also applied, except for the separated automated lane since this is just one lane. At this scenario also 20% of the vehicles take the highway exit and the AVs that do not have to take the upcoming highway exit stay on the dedicated lane.

Limited Access Lane with buffer (LAL): This model is modelled exactly the same as the LABL model, there is solely a difference in the parameters that are used for the THW based on the observed parameters in the driving simulator research.

Continuous Access Lane (CAL): In this model the AVs can enter and exit the dedicated lane whenever they desire. After a normal three lane section (just like the other models) the most outer left lane gets a restriction for MVs and the AVs prefer the most left lane since the 'slow lane rule' is applied, which is the case on the highway system in the Netherlands where you take over cars on the left. This implies that AVs form platoons on the left lane but still have the possibility to merge into the middle lane if this is necessary for a desired lane change. At this scenario 20% of the vehicles will take the highway exit at the end of the road.

Besides the four road design models there are also other aspects of the models that are tested in VISSIM. These road design scenarios were tested with different vehicle compositions, traffic intensities, lane changing distances and lengths of the weaving section. These parameters are explained in the following sections and an overview of the different combinations of models that were run in VISSIM is provided in Table 6-1. Parameters and levels used. An overview of all the combinations can be seen in Appendix G.

Table 6-1. Parameters and levels used

Parameter	Levels
Road design Scenario	BL, LABL, LAL and CAL
Traffic intensity	5500 veh/h and 5000 veh/h
Penetration rates of AVs	10% - 50%, in steps of 5%
Different weaving section lengths	600m, 800m and 1000m
Lane change distance	200m – 1200m, in steps of 200m

6.1.1 Vehicle composition

Since the effect of trucks was not taken into account in the driving simulator research there are only two vehicle types used in this traffic flow model, automated vehicles and manual vehicles. The penetration rate of these vehicles over time is still unknown as debated in section 2.1.2. Logically a penetration rate of 33.3% of AVs on the total traffic flow would be sufficient for the traffic flow when one lane of a three-lane road is converted to a dedicated lane for AVs. This model was tested for scenarios with a penetration rate varying from 10% to 50% and data was retrieved in steps of 5%.

6.1.2 Traffic intensity

An important factor that influence the results is the Traffic input of the road section. The traffic intensities on the highways in the Netherlands are quite high in comparison with other countries. In 2014 the highest traffic intensity was at the A13 (a three-lane highway) with a value of 5.836 vehicles per hour, the A10 was the second highest traffic intensity with 4.374 vehicles per hour. In 2014, an average of 2,268 motorized vehicles per hour covered Dutch highways (Central Bureau of Statistics Nederland, 2014). Therefore, multiple scenarios were run with a variety of traffic intensities. Scenarios were tested with traffic intensities from 4000 vehicles per hour to 5500 vehicles per hour. With 4000- and 4500 vehicles per hour the traffic flow was approximately stable over the different penetration rates of AVs and therefore the scenarios with a traffic intensity of 5000 and 5500 were investigated. Also keeping in mind that the road network is getting more and more crowded, therefore these values are interesting to be investigated.

6.1.3 Lane change distance

A calibration and validation study of the models in VISSIM indicated that one of the sensitive parameters for traffic flow modelling is the lane change distance (Woody, 2006). The lane change distance in VISSIM is the distance a vehicle becomes aware of the fact that it has to reach a certain connector and starts searching for a lane change possibility to reach that destination connector (Fellendorf & Vortisch, 2001). In the case of this model it is for example the distance an AV becomes aware that is has to change to the dedicated lane. Nevertheless, the logic behind the lane changes in VISSIM is a bit more complicated than just a lane changing distance. The lane change is based on gap acceptance of the vehicles in the model. It is all related with the accepted deceleration, if a driver is willing to accept that he forces a lag vehicle on the desired lane to decelerate or not (Fellendorf & Vortisch, 2010b). This accepted deceleration is as well a parameter as a function of the distance to the emergency stop.

Research (Fellendorf & Vortisch, 2010a; Vortisch, 2014) indicates that a suitable distance is approximately 700 meter with emergency stop of 50 m for the off-ramp connector. Because of the sensitivity of the lane changing distance multiple scenarios were ran with different lane changing distances (200-, 400-, 600-, 800 and 1000 meter). Unfortunately, in the VISSIM software it is not possible to automatically run a model with a distribution for the lane changing distances. Therefore, this analysis was done manually, with each time changing the lane changing distance value.

6.1.4 Driving behavior parameters

Section 2.4.2 already gave some insights in the models that could be used for modelling driving behavior in VISSIM. Insights were provided in the logic behind the car following and lane changing models in VISSIM and the necessary adaptions to model AVs.

The car-following behavior of manual vehicles (MV) in VISSIM is modelled according to the model by Wiedemann 99. In order to model the AV car-following behavior, some adaptions to the modeled driving behavior that is used for the MVs was done. The differences in the lane changing model between the MVs and the AVs is only expressed by the cooperative lane changing parameter. Furthermore, the AVs do not have the ‘slow lane rule’ but the ‘free lane selection’ as general behavior, because on the dedicated lane the AVs does not have to choose a lane. The actual parameters that are used to model the car following behavior and the lane changing behavior of the MVs as well as the AVs can be seen in Figure 6-1-Figure 6-3. These parameters are based on a literature review and calibration of the models and are derived from Table 2-3.

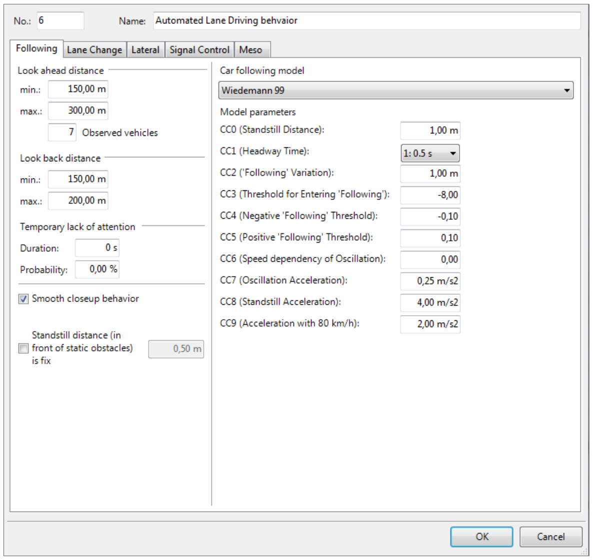


Figure 6-1. Following behavior parameters AVs

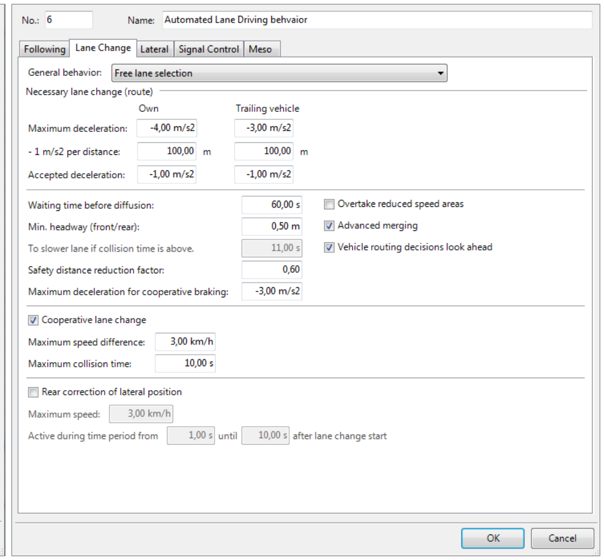


Figure 6-2. Lane Change behavior parameters AVs

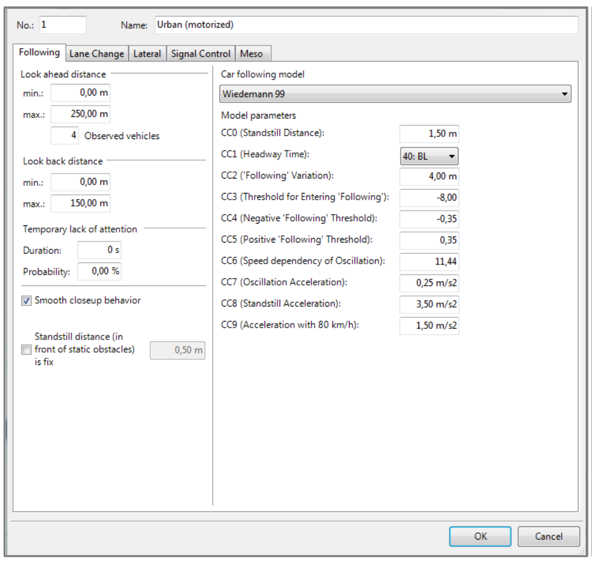


Figure 6-3. Following behavior parameters MVs

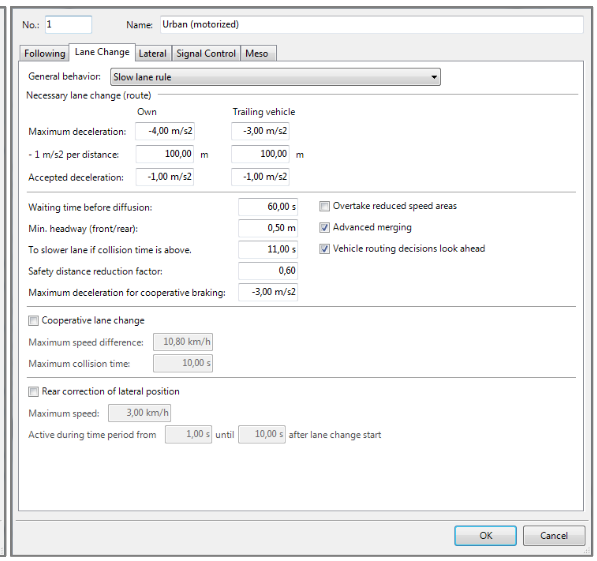


Figure 6-4. Lane Change behavior parameters MVs

6.1.5 Time headway

The time headway for the AVs will be set to a value of 0.5s. This value is commonly used in the literature (section 2.4.3) as a reasonable time headway for automated and connected vehicles and this value is also used in the driving simulator study as the distance AVs kept from the vehicle in front of them.

In order to set the right value of the parameters for the THW for the MVs in the different models a small adaption to the observed parameters of the driving simulator experiment were made. The THW observed in the driving simulator varies between 2.5 and 3.2 seconds which is very high compared to commonly observed values in real life in the Netherlands. This is the desired THW the participants choose in free flow situation which exceeds the THW observed during rush-hour or heavy traffic. Similar results were found in the literature; the observed THW values in free flow situations on the middle lane of a highway (Ayres, Li, Schleuning, & Young, 2001) as well as in the driving simulator experiment by (Gouy, 2013) an average THW of 3.31s and 3.39s was observed. These values would be in line with the observed value in the driving simulator for the baseline measurement where the participants were not influenced by the short THW kept by the platoons. Nevertheless, for the purpose of traffic flow modelling these values could not be applied and the impact on a free traffic flow is not what would be interesting to test. Therefore, the parameters have to be transformed to reasonable parameters for highly pressured traffic situations.

As stated in the literature review in section 2.4.3, the reasonable THW for manual driving is 1.64s (Nowakowski et al., 2010; Shladover et al., 2012)(Nowakowski et al., 2010), while the average observed THW in the Netherlands is lower reaching a value of 0.9s (Swov, 2008). As can be seen in Table 6-2 the observed values from the driving simulator have been transformed to the standards found in the literature. Since the transformed values with a baseline of 0.9s are unreasonably low, with values virtually reaching the AV THW of 0.5s, a baseline value of 1.64 is used for these models.

Table 6-2. THW parameters

Scenario	Average THW observed in driving simulator (s)	% difference if BL is 1	When 1,64 is BL	When 0,9 is BL
Baseline Scenario (BL)	3,2407 s	1	1,64	0,9
Limited Access Barrier Lane (LABL)	3,1710 s	0,9785	1,6047	0,8806
Limited Access Lane with buffer (LAL)	2,6974 s	0,8324	1,3651	0,7491
Continuous Access Lane (CAL)	2,4793 s	0,7651	1,2547	0,6885

6.1.6 Length of weaving section

According to the Dutch Road Standards the length of a weaving section should be approximately around the 600 to 700 meters (Goemans et al., 2011; "Richtlijn Ontwerp Autosnelwegen 2017," 2017). Because these weaving sections are a crucial part of the design, the models were tested with different weaving section lengths (600-, 800- and 1000 meter). Since these weaving sections could become bottlenecks when the penetration rate of the AVs is increased it is interesting to test whether a longer weaving section might be beneficial for the traffic flow.

6.1.7 Length of off-ramp

The length of the off-ramp, where 20% of all vehicles exits the highway in all the models, has a length of 300m, this is according to the Dutch Road Standards of 2017 ("Richtlijn Ontwerp Autosnelwegen 2017," 2017).

6.2 Results

In this section the results from the traffic flow simulation models developed in VISSIM are discussed. The impact on the traffic flow and average travel time are presented and discussed for all the four road design scenarios (Baseline Scenario (BL), the continuous access lane (CAL), limited access lane with buffer (LAL), and the limited access barrier lane (LABL)). An overview of these models and the corresponding lane restrictions is presented in Table 6-3. The models are tested with different traffic intensities, various penetration rates, different lengths of weaving sections and various lane change distances.

Table 6-3. Overview road design scenarios and lane restrictions

Road design scenario	MVs	AVs
Baseline Scenario (BL)	Are able to drive on every lane	Are able to drive on every lane
limited access barrier lane (LABL)	Are only able to drive on the outer right lane and the middle lane	When there is a dedicated lane they have to take this lane
limited access lane with buffer (LAL)	Are only able to drive on the outer right lane and the middle lane	When there is a dedicated lane they have to take this lane
the continuous access lane (CAL)	Are only able to drive on the outer right lane and the middle lane	Are able to drive on every lane but preference for the outer left lane

Figure 6-5 and Figure 6-5 present the traffic flow [veh/h/l] for as well a traffic intensity of 500 veh/h and a traffic intensity 5500 veh/h. As can be seen the traffic flow improves for both traffic intensities when there is a dedicated lane for AVs.

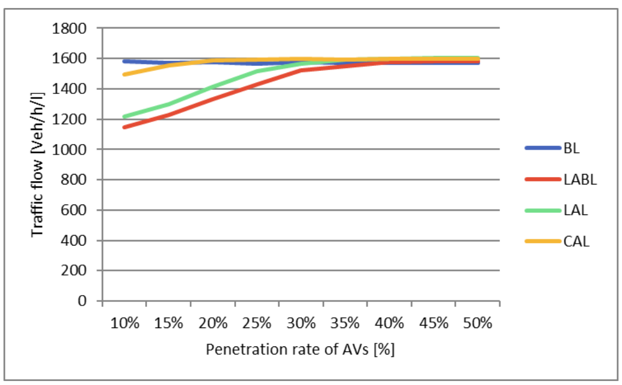


Figure 6-5. Traffic flow with traffic intensity of 5000 veh/h

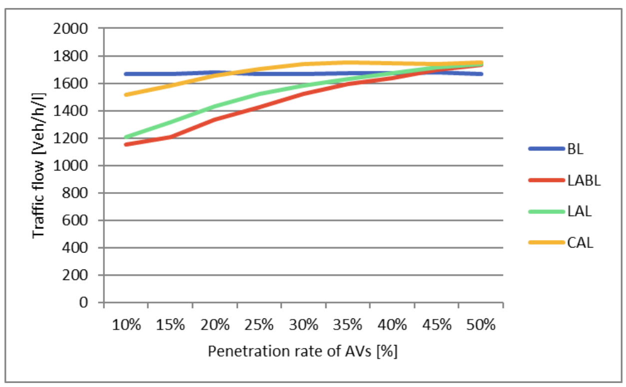


Figure 6-6. Traffic flow with traffic intensity of 5500 veh/h

The results of Figure 6-5 and Figure 6-5 with a traffic intensity of 5500 veh/h and 5000 veh/h are based on a lane changing distance of 800 meter (the distance vehicle know upfront when they have to make a lane change) and a weaving section of 600 meter. Logically the traffic flow for the scenarios with a smaller traffic intensity are all smaller. At smaller penetration rates of AVs the traffic flow of the models with a dedicated lane are smaller than the baseline model. The graph shows that the traffic flow of the CAL Model started climbing steadily and flattened out at a penetration rate of 30%. This pattern is similar for the LABL and the LAL model, but they solely reach their optimum at higher levels of penetration. The difference between the graph in Figure 6-5 and Figure 6-5 is that with a lower traffic intensity the maximum traffic flow capacity is already reached in an earlier stage of penetration. Nevertheless, it is visible with both penetration rates that the tipping point in which the CAL model improves over the baseline model is far before the expected 33.3%. At penetration levels between the 15- and 20% the overall traffic flow is already improved in the CAL scenario over the baseline scenario, for both traffic intensities 5500 and 5000 veh/h.

6.2.1 Lane change distance

As already discussed in section 6.1.3, the lane changing distance is a sensitive parameter. Therefore, this parameter was tested at different levels. The initial lane changing distance of 800 meter appeared to be a very suitable lane changing distance in comparison with the other values that were tested. An improvement of the traffic flow was expected when the lane changing distance was increasing to 1000- or 1200 meters. Nevertheless, the traffic flow remained approximately the same with an increase or decrease within a range of 0-3%.

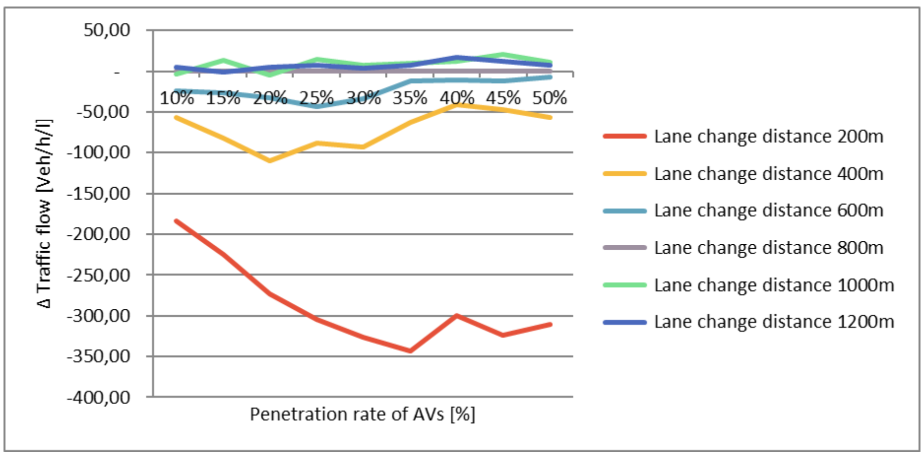


Figure 6-7. Average change in Traffic flow per lane changing distance compared to the lane change distance of 800m

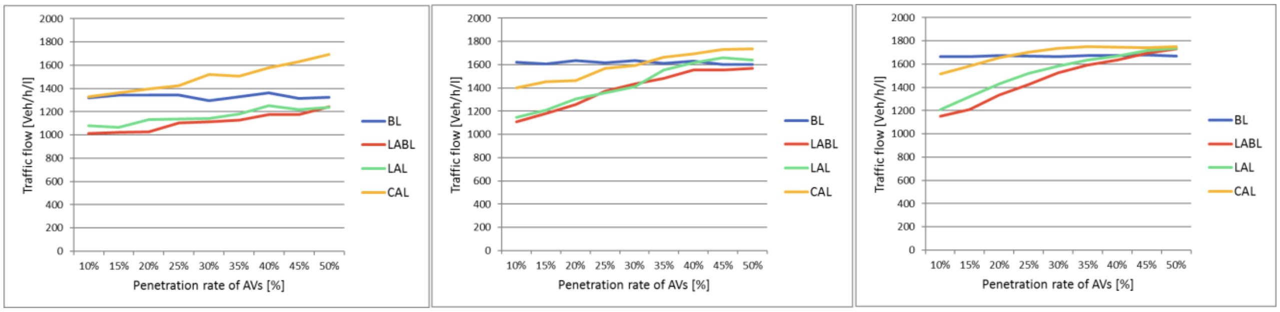
Figure 6-7, presents the average difference in the traffic flow with regard to the lane change distance of 800 meter, over all four road design scenarios and for both traffic intensities of 5500 and 5000 at different penetration levels. It can be seen that the larger the lane changing distance is, the bigger is the improvement in traffic flow. The similarities over these different lane changing distances support the models' robustness and insensitivity to model parameters. When the traffic flow results would change dramatically when one parameter was changed would imply a highly sensitive model with no robust results. The traffic flow really changes when the lane changing distance is decreased to an extraordinary small value of 400 meters (average decrease of 5%) or 200 meters (average decrease of 18%). It appears that when the lane changing distance reaches a certain sufficient value, an increase of the lane changing distance does not affect the traffic flow significantly. When the impact of the lane changing distance is investigated over the four different scenarios, as presented in Table 6-3, it becomes clear that this is the most influential variable for the LABL and LAL model.

Table 6-4. Average percentile changes in Traffic flow per lane changing distance per scenario relative to the 800m lane changing distance

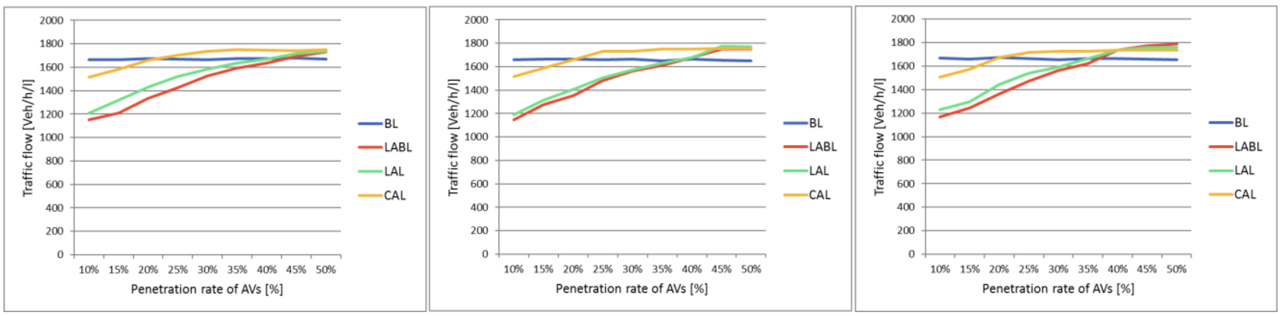
Scenario	**200m**	**400m**	**600m**	**800m**	**1000m**	**1200m**
BL	-18%	-2%	-1%	0%	0%	-1%
LABL	-23%	-5%	0%	0%	2%	3%
CAL	-10%	-5%	-3%	0%	0%	-1%
LAL	-23%	-6%	-2%	0%	0%	1%

As can be seen in Table 6-4 the highest differences are visible within the LABL and the LAL scenario (in bold). This is a logical result since these models have the most static routing decisions and therefore are more affected by the lane changing distance.

Moreover, an interesting effect that becomes clearly visible when all the traffic flow graphs are represented together is the steepness of the LABL and LAL lines. Both lines of the LABL and LAL are quite similar, and when the lane changing distance increases, the steepness of these two lines increase as well. As the lane changing distance increases the intersection of the LABL and LAL lines with the baseline line is shifted forward. This implies that the tipping point of improving the traffic flow for the LABL and LAL scenario over the Baseline scenario changes to a lower penetration rate of AVs as can be seen in Figure 6-8. Both lines do not intersect at a lane changing distance of 200 meters, are intersecting around the 40 to 45% at 600 meters, and with a 1200 meter lane changing distance the tipping point is already reached around 35%. A similar effect is visible for the CAL model, the steepness of the line increases until 600 meters and afterwards remain constant. The results in Figure 6-8 are based on a traffic intensity of 5500 vehicles per hour, for the traffic intensity of 5000 veh/h a similar result is visible and these graphs are shown in Appendix H.



a. Lane changing distance of 200m *b. Lane changing distance of 400m* *c. Lane changing distance of 600m*



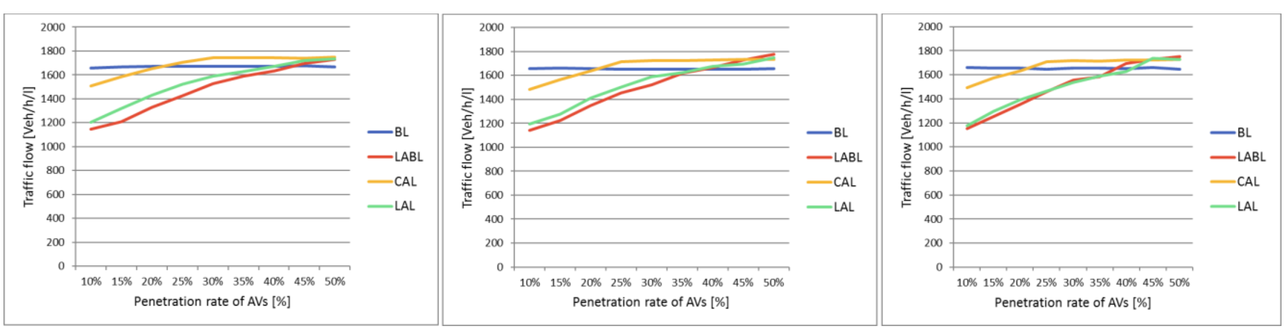
d. Lane changing distance of 800m *e. Lane changing distance of 1000m* *f. Lane changing distance of 1200m*

Figure 6-8. Traffic flow over different Lane Changing Distances

Based on these findings the conclusion can be drawn that regarding the lane changing distance a robust and insensitive model was developed that is only affected when lane changing distance are decreased to extraordinary low values. When the lane changing distance has reached a certain value it does not affect the results of the total traffic flow extensively.

6.2.2 Length of the weaving section

Another aspect that was expected to have influence on the results is the length of the weaving section, which is crucial to the lane changing maneuvers from and to the dedicated lane. A logical hypothesis would be that with increasing the length of the weaving section the traffic flow would be improved. Unfortunately, this hypothesis should be dismissed. All four scenarios were tested over all penetration rates and it appeared that there is more or less no change in the results.



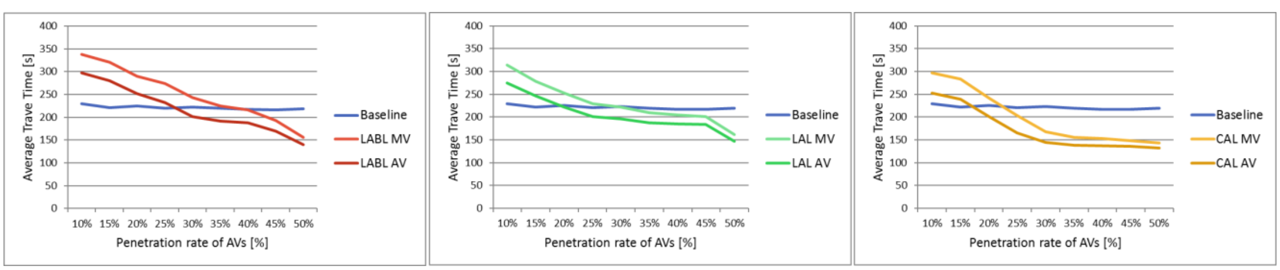
a. Weaving section length of 600m *b. Weaving section length of 800m* *c. Weaving section length of 1000m*

Figure 6-9. Traffic flow over different weaving section lengths

As can be seen in the traffic flow graph of all 3 weaving section lengths in *a. Weaving section length of 600m*
b. Weaving section length of 800m *c. Weaving section length of 1000m*
Figure 6-9 it becomes clear that the traffic flow isn't influenced significantly by the length of the weaving section. For all three weaving section lengths the improvement of the traffic flow per scenario over the baseline scenario remains more or less the same. The total length of the investigated road sections is slightly different in the models because of the increased length of the weaving section, therefore solely looking at the traffic flow might not be sufficient enough, although the length difference is relatively small. Nevertheless, it also appeared that there is no significant change in the average speed when the weaving section length is increased. The weaving section of 800 meter as well as the weaving section of 1000 meter have an average speed increase of 2% over the weaving section of 600 meter. These differences do not significantly influence the results which is in line with the conclusion drawn in section 6.2.1; if the length for possible lane changes is sufficient enough, an additional increase in the length does not have that much influence on the total traffic flow. With regard to the lane changing distance the conclusion was drawn that after a lane change distance of 600 meter increasing the length didn't have a significant impact on the traffic flow, this would also be applicable for this situation. When the length of the weaving section reached a sufficient length for conducting lane changes, increasing this length does not actually influence the total traffic flow. Therefore, the standards for weaving sections which are currently used by the Dutch Road Authority are sufficient for weaving sections of dedicated lanes for AVs.

6.2.3 Differences AVs and MVs

It has been shown that the traffic flow was improved because of the dedicated lane. It is important to also investigate if the benefits are not only for AVs but also for MVs. It might be a possibility that the traffic flow on the dedicated lane is improved to such an extent that it might cover the decrease in traffic flow for the MVs, so the overall traffic flow is still improved. Obviously, this is not a desirable outcome from equity point of view, and therefore these differences should also be investigated.



a. Difference LABL Model *b. Difference LAL Model* *c. Difference CAL Model*
Figure 6-10. Average Travel Time per scenario per vehicle type

a. Difference LABL Model *b. Difference LAL Model* *c. Difference CAL Model*
Figure 6-10 shows the average travel time per vehicle type per scenario over the different penetration rates of AVs. These graphs represent a traffic intensity of 5500 vehicles per hour, for the traffic intensity of 5000 veh/h similar results were found. In these graphs it becomes clear that MVs do not suffer under the implementation of a dedicated lane and the decrease in travel time shows a similar pattern for both vehicle types. It is important to keep this in mind when a dedicated lane will be implemented. Within these

graphs it is also clear that the traffic flow is improved for MVs at a higher penetration rate in comparison with the AVs. And the same percentages are visible as mentioned before, for the CAL model around the 20% and for the LABL and LAL models around the 30-35% penetration.

6.3 Conclusion and discussion

In conclusion it can be stated that a dedicated lane for AVs will have a positive influence on the traffic flow for the highway in the Netherlands from a certain penetration rate. Regarding the continuous Access Lane (CAL) the traffic flow is improved with the lowest penetration rate. Based on the previous results, an improvement of the total traffic flow for the CAL model over the Baseline model can already be observed for penetration rates between 15- and 20%. While this improvement is visible for the limited access lanes between the 30- and 35%. This result lies in the fact that this model has the benefit of throughput on the dedicated lane without the losses of obligatory lane changes in the entry and exit section of the dedicated lane. Furthermore, it was concluded that once the lane changing distance reaches a sufficient value (>600m) an increase of this distance does not affect the traffic flow suggestively. Moreover, it was also concluded that an increase in length of the weaving section does not affect the traffic flow either. This resulted in the conclusion that the standards which are currently used by the Dutch Road Authority for weaving sections could also be applied for a dedicated lane for AVs.

The methodology that is used for this research is a method that is widely used in the literature and is suitable for assessing the impact on traffic flow. Using such a simulation software is very useful to get insights on traffic flow when changing design scenarios in a controlled environment, nevertheless these models are also based on numerous assumptions. Assumptions that are made regarding the modelled driving behavior were derived from the literature, assumptions about lane changing distances, vehicle traffic intensity, length of the weaving section, and length of the off-ramp are all incorporated in the traffic flow models. These assumptions are made carefully and based on thorough literature research but are still assumptions that are sensitive for changing values. To test the validity and robustness of the model and vehicle input, models with different lane changing distances and weaving section lengths were tested. These different models resulted in similar traffic flow results which supports the robustness of the model. One aspect that should be pointed out in this model is that the THW that is adopted from the parameters measured in the driving simulator research are applied for all the MVs that were driving next to the dedicated lane, as well the middle or the right lane. The effect that is measured is solely measured for MVs that were driving directly next to the platoon and not when there was another lane separating them. Due to limitations in the model it was not possible to make the distinguishing of THW per vehicle type that drives on a specific lane and therefore it is assumed, since the vehicles change lanes continuously their adapted driving behavior is applicable for both lanes. This is an aspect that might be improved in further research.

7.0 Conclusion and discussion

In this chapter the concluding remarks on this research are elaborated upon. This chapter includes what can be learned from this research and which insights are provided, the limitations of this research, the recommendations for further research and the gained insights which can be applied into practical recommendations for Rijkswaterstaat.

7.1 Findings

Firstly, the design of the dedicated lane was explored based on the state of the art literature on this topic. This provided answers to the first sub question: "*How should a dedicated lane for automated vehicles be designed? On which side of the road? Completely separated or not? What is the state of the art on this topic?*".

Since the 90's in the field of automated highway systems, a dedicated infrastructure for automated vehicles, has been explored. This field in combination with current dedicated infrastructure systems such as HOV lanes and the expert knowledge of the Dutch Road Authority, provided input and references for the infrastructural design of the dedicated lane for automated vehicles. With regard to the positioning of the lane, the literature often refers to the left side of the road for left-hand traffic (Hall & Caliskan, 1997; Ran et al., 1999). This is substantiated by logical reasoning, when the lane would be placed in the middle or on the right side of the highway regular traffic would have to interfere with the dedicated lane when a highway exit has to be taken. Furthermore, the left side would be the most logical position based on the assumption that the throughput of an automated lane would be higher than the throughput of lane for MVs and the right-side rule is applied on the highway in the Netherlands. Furthermore, the access to- and from the dedicated lane was also investigated. Literature regarding automated highway systems suggests barriers between the dedicated lane and the regular traffic to overcome collisions and interruption in the continuous flow. Nevertheless, in safety researches regarding HOV-lanes in Canada, there are no safety advantages found of limited access lanes over continuous access lane. Traffic flow modelling found substantial differences regarding the accessibility of the lane and the throughput. The dedicated lane for AVs improves the traffic flow once a penetration rate of 15-20% for the Continuous Access Lane, while the traffic flow is only improved around 30-35% for the Limited Access Lane. Regarding efficiency, the continuous access lane is highly favorable over the limited access lane with a barrier or a buffer. However according to qualitative data collected in the post experiment questionnaire there are some concerns regarding the perception of safety. Furthermore, the behavioral adaptation of manual vehicles on lanes next to the Continuous Access Lane might threaten safety benefits. Since the THW of drivers in the Netherlands is already extraordinary low (0.9s). Further decreasing this value due to the appearance of platoons in the frame of reference of manual drivers, which is observed in the driving simulator experiment, might conflict with the traffic safety. Therefore, it is strongly recommended that the aspect of safety should be further investigated in follow-up research. Solely based on the findings of this study the conclusion can be drawn that the continuous access lane on the left side of the road is the most desirable infrastructure design for a dedicated lane for AVs on the highway in the Netherlands from the traffic efficiency perspective.

Secondly drivers' behavioral changes of the human-driven vehicles were investigated. These changes were measured in a driving simulator experiment and provided us with interesting insights. Which provided answers to the second sub question: "*How does drivers' behavior of the human-driven vehicles will be influenced when driving in proximity to a dedicated lane (of different characteristics) for automated vehicles?".*

There is an observed behavioral adaptation in drivers' behavior of manual vehicles when they are in the proximity of platoons of AVs. Moreover, it can also be concluded that the type of separation of this lane also has an influence on the behavioral adaptation of MVs in the proximity of platoons of AVs. Statistically significant mean THW differences have been observed with regard to the baseline measurement (M = 3.24, Std. = 1.56) and within the three road design scenarios, the continuous access lane (M = 2.48, Std. = 1.26), limited access lane with buffer (M = 2.70, Std. = 1.33) and the limited access barrier lane (M = 3.17, Std. = 1.56). The interesting fact was that people adjust their THW when they are driving in the direct proximity of a platoon but maintain a larger THW, similar to the baseline measurement, when they are separated by a guardrail. The measurements that were observed in the driving simulator were measured in the free-flow situation and are therefore relatively high values. When this observed behavioral adaptation is translated to parameters with a more reasonable THW for higher traffic intensities that are measured in the Netherlands (THW = 0.9s), the adapted THW for the continuous access lane and the limited access lane could interfere with the traffic safety.

The sociodemographic factors that appeared to have significant influence on the THW were number of years of driving experience and gender. The fact that gender was influential wasn't surprising and is broadly supported by literature, but the influence of number of years of driving experience could not be supported by literature. Nevertheless, these sociodemographic variables were also included in the Linear Mixed Model and the relationship was in this model not statically significant. This could be explained by the small sample of 34 participants. This provided an answer to "*Which socio-demographic characteristics have influence on the THW?*".

Fourthly, the parameters to model mixed traffic situations were investigated. Literature was examined to give insights on the parameters that were used to model MVs and AVs in VISSIM. A Wiedemann-99 car-following model was used to model MVs and was used as a basis that was further adapted to model AVs. This adaption was based on the parameters that can be found in Table 2-3 in section 2.4.2. This provided answers to the sub research question: "*Which parameters in the car-following and lane-changing models need to be calibrated to simulate mixed traffic?".*

All these aspects mentioned above were combined into traffic flow modelling that would result in the answer on the final sub question: "*At which penetration rate of AVs will the traffic flow be improved by the implementation of a dedicated lane?"*. The adopted THW for the different road design scenarios was used as THW parameters in the traffic flow models when the MVs were driving next to the platoons on the corresponding road design scenarios. These models were tested with different traffic intensities, penetration rates of AVs, lane changing distances and different weaving section lengths. It was concluded that once the lane changing distance reaches a sufficient value (>600m) an increase of the lane changing distance does not affect the traffic flow suggestively. Moreover, it was also concluded that an increase in length of the weaving section does not affect the traffic flow either. The standards which are currently used by the Dutch Road Authority are applicable for a dedicated lane for AVs. A dedicated lane for AVs will have a positive influence on the traffic flow for the highway in the Netherlands when a certain penetration rate of AVs is reached. Regarding the continuous Access Lane, the traffic flow is improved over the baseline scenario once a penetration rate of 15-20% is reached. While in the scenario of the Limited Access Lanes the traffic flow is improved at penetration rates around 30-35%.

Combining the information provided for all the sub research questions gives answer to the main research question of this thesis: “***How is drivers’ behavior influenced by the implementation of a dedicated lane for automated vehicles on the highway in the Netherlands and what are the implications on traffic flow efficiency?***”.

Therefore, it can be stated that drivers’ behavior is influenced by the implementation of a dedicated lane for AVs on the highway in the Netherlands by a reduced THW and Traffic efficiency is improved when penetration rates from 15% to 20% are reached for a continuous access lane.

7.2 Scientific relevance

This study enhances academic understanding about the implications of a dedicated lane for automated vehicles on the highway in the Netherlands. This thesis supports this field of research and was able to fill in the knowledge gap. It gave insights into the implications of the four proposed infrastructure design scenarios and provided answers to the proposed research questions. Nevertheless, where it provided answers, it also resulted in the need for answers to new relevant research questions for this topic. The objective of this study was to get more insight in the implications of such a lane regarding behavioral adaptation and traffic flow efficiency and this is obtained.

This study combined a driving simulator study and traffic flow modelling. The combination of these two methods is the strength of this thesis which makes it able to give a broad range of insights on the implications of a dedicated lane. Also, the traffic flow influence of AVs on highway systems is studied in earlier studies, but the behavioral adaptation of MVs is not considered in these studies. The result of this study provides insight on the implications of a dedicated lane for automated vehicles and supports the research already conducted. Behavioral adaptation of drivers of manual vehicles is not something that should be forgotten. This thesis offers the Dutch Road Authority the first steppingstones in developing policy regarding the implementation of automated vehicles on the Dutch highway system.

7.3 Societal relevance

The societal relevance of research in the field of AVs and its effects on the transportation network are thus to avoid foreseeable negative effects and make the implementation of this disruptive technology a seamless process. Investigating and helping to improve the mobility networks in the Netherlands is crucial to its economy and society. This thesis gave the first insights into the implications of a dedicated lane for automated vehicles on the highway in the Netherlands. As was predicted it will take some time before such a lane will actually be implemented, the technology and the adoption of AVs have to make a leap forward first, but when this is the case, it is crucial that the implications for such a lane on traffic flow and safety have already been explored. These insights can provide the Dutch Road Authority with the first steppingstones to make the infrastructure futureproof.

7.4 Limitations and Recommendations

The weaknesses of this thesis are pointed out at the discussion sections of the previous chapters. Here it is pointed out that there are some aspects that could be improved in this research. The driving simulator had some limitations which resulted in some aspects of the driving environment that could be improved. Traffic on the most right lane of the infrastructure, some variation in the model with regard of the infrastructure design and more cars on the road are aspects that could be improved. The traffic flow models are based on assumptions, which is always an aspect that could be improved. Furthermore, as discussed in section 6.3, the adopted THW for MVs are in these models also applied on the most right lane while this is not investigated in the driving simulator study. A limitation of this study is that the parameters measured in the driving simulator are measured in free flow traffic and not in higher traffic intensities. Converted parameters of these observed values are used in the traffic flow models but observed values in highly pressured road networks would always be more realistic.

There are still a lot of research gaps that could be identified regarding the relation between automated vehicles and the infrastructure. The results obtained in this study also still pose opportunities to expand and explore the implications of the implementation of a dedicated lane. Specifically based on this research, the gaps that were identified are the following.

The adoption rate of automated vehicles is still unclear and more insights in this topic could be provided. The attitude of society toward these technologies, an overview of existing technologies and the adoption of current (semi)automated technologies combined would provide a better understanding of possible penetration in the future.

Another interesting recommendation for further research is to investigate whether people also adapt their THW in a more highly pressured road network. In the driving simulator study people were tested in a free traffic flow situation in the appearance of platoons, it would be interesting if people also adapt their THW in a highly pressured road network, which is most of the time the case in the Netherlands. This could provide us with more insight regarding safety issues since the observed THW in pressured traffic observed in the Netherlands is already exceptionally low. An example would be a study with emergency braking or reaction time to test if the decrease THW is indeed too short for drivers of manual vehicles.

The issue of safety, which is also a big indicator in the previous recommendation, is also an aspect that should be investigated in further research. Both the implications for the objective- as the subjective safety would be interesting for further research. A shorter THW might be at stake of the safety perspective, but this perspective should be investigated at a broader level. In the post-questionnaire participants declared that they felt unsafe driving directly next to a platoon, reasoning behind this is lacking and follow up research would also here be desirable.

Additionally, the merging area of the dedicated lane is an aspect full of further research questions, what exactly happens here, how platoons are formed, how do drivers of manual vehicles react to AVs merging out of the dedicated lane, more insights into the process of connecting AVs in relation with the infrastructure and AVs entering the highway.

Furthermore, this research is conducted with people between the age of 20 and 30, in general is this younger age category more technology oriented and open to new technological developments, this also resulted from the questionnaire. Further research on behavioral adaptation of more older participants who are more reluctant toward technological developments would be interesting.

7.5 Recommendation for the Dutch Road Authority

For the recommendation for the Dutch Road Authority, Rijkswaterstaat, it is important to take all the aspects of this research into account. The most important criteria for the Dutch Road Authority are safety, costs, flexibility, efficiency and durability which has been stated in their network-operation-vision. When last four criteria are evaluated it becomes clear that the Limited Access Barrier Lane (LABL) is the most unfavorable option of the four scenarios that are tested in this thesis.

Implementing a guardrail in the highway system is very expensive and counterproductive for the flexibility of the Dutch road system. The Road Authority is trying to increase the flexibility over the past years (Rijkswaterstaat, 2017a) and is unbundling (Van Loon, Walhout, & Van Der Velden, 2015) its infrastructure. This means making the infrastructure as less complicated as possible to make it adaptable for the future. Implementing such a guardrail would be inefficient and not durable since it is still uncertain what the future will bring regarding automated vehicles. A dedicated lane for AVs might already improve the traffic flow once a penetration rate of 15-20% is reached for the Continuous Access Lane (CAL) and around 30-35% for the Limited Access Lane and is still improved over the baseline when penetration rates of 50% are reached, but at higher penetration rates two lanes for AVs might be desirable instead of one lane. Since it is still unclear when such levels of penetration will be reached, implementing a guardrail is inflexible, expensive and ephemeral.

Nevertheless, there is always the unending paradox traffic engineers have to face of moving people as efficiently as possible and getting them there safely. Although the efficiency, flexibility and durability might insinuate a continuous access lane without any barrier safety issues might provide a different perspective.

14.2% Of the participants indicated in writing that they felt unsafe when they were not separated by a guardrail when the platoon was directly next to them. Also, when the participants were asked at which situation they felt the more safe 66.7% answered the situation with the guardrail. Because of the small sample of 35 participants who drove the four scenarios in the driving simulator it is hard to draw valid conclusions. Despite this small sample, these results might be good indicators that should be considered. These indicators are only based on subjective safety and no evidence-based research is conducted about objective safety. Therefore, further research is desirable to further understand these concerns. Also, the THW adaption of the driving behavior as measured in the CAL and the LAL scenario result in behavioral changes that might threaten safety benefits. Since the THW of drivers in the Netherlands is already extraordinary low, further decreasing this value due to the appearance of platoons in the frame of reference of manual drivers might be at stake with the traffic safety. Therefore, the entire aspect of safety might be an interesting cornerstone for further research.

Therefore, in the perspective of the Dutch Road Authority with regard to traffic efficiency, durability and flexibility a continuous access lane is the most desirable. This lane might be flexible and expandable if the penetration rate increases on the highway in the Netherlands. Nevertheless, safety concerns for such a lane might be apparent and therefore follow-up research regarding this lane is highly recommended.

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Appendix

A. Screenshots of the four models developed in Unity

B. Questionnaire used

Survey Simulator Experiment Automated Vehicles

This survey should be conducted before participating in the driving simulator experiment
Deze enquête moet worden ingevuld alvorens deel te nemen aan het rijsimulator experiment.

*Vereist

1. **E-mailadres** *

____

Name or Reference Participant Number / Naam of Experiment Deelname referentie nummer

If you are willing to enter your name, or do not know your Reference Participant Number (yet) the data from this survey will be handled discrete, after coupling the experiment data with the survey data the name will be erased from the data set and will be made anonymous. If you are not willing to enter your name and do not know your Reference Participant Number please contact +31637332588.

Wanneer u zich (nog) niet bewust bent van uw Experiment Deelname Referentie Nummer en bereid bent u naam op te geven zal de data uit deze enquête discreet behandeld worden. Na het koppelen van uw gegevens aan de resultaten uit het simulator experiment zal uw naam verwijderd worden uit de data en zal de dataset geanonimiseerd worden. Wanneer u niet bereid bent u naam op te geven en u zich niet op de hoogte bent van uw Experiment Deelname Referentie Nummer kunt u contact opnemen met +31637332588.

2. **Name or Reference Participant Number / Naam of Experiment Deelname referentie nummer** *

____

Personal data / Persoonsgegevens

3. **Gender / Geslacht** *

Markeer slechts één ovaal.

- ( ) Male / Man
- ( ) Female / Vrouw
- ( ) Other / Anders

4. **Year of birth / Geboortejaar** *

Markeer slechts één ovaal.

- 1917
- 1918
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- 2000

5. **Do you have a valid driving licence? / Bent u in het bezit van een geldig rijbewijs?** *
Markeer slechts één ovaal.

- Yes / Ja
- No / Nee

6. **Do you have a car? / Heeft u een auto?** *
Markeer slechts één ovaal.

- Yes / Ja
- No / Nee

7. **Number of years of driving experience on the Dutch Roads / Aantal jaren rijervaring op Nederlandse wegen** *

Markeer slechts één ovaal.

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8. **Nationality / Nationaliteit** *

9. **Did you ever drive in a driving simulator before? / Heeft u al eens eerder in een rijsimulator gereden?** *

Markeer slechts één ovaal.

- Yes / Ja
- No / Nee

Technology orientation / Technologisch georiënteerd

10. **I am very Technology oriended? / Ik ben erg technologisch georiënteerd** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

11. **I believe Technological developments will have a postive influence on society / Ik geloof dat technologische ontwikkelingen een positieve invloed hebben op de maatschappij** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

Automated Vehicles/Autonome Voertuigen

Automated vehicles are vehicles that are able to drive on their own without any human imput. This vehicle is able to drive based on observations of the surroundings and information provided by other vehicles on the road and the infrastructure itself. / Autonome voertuigen zijn voertuigen die geheel zelfstandig kunnen rijden zonder menselijk ingrijpen. De auto kan zelf rijden op basis van het detecteren van zijn omgeving en informatie die hij krijgt van andere voertuigen op de weg en de infrastructuur zelf.

12. **I believe the Automated vehicle will have a positive impact on society / Ik geloof dat de autonome auto een positieve invloed zal hebben op de maatschappij** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

13. **I would only drive an Automated vehicle on less complicated infrastructure situations such as highways / Ik zou alleen in minder complexe situaties, zoals de snelweg, in de autonome auto rijden** *
Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

14. **I am willing to drive an Automated vehicle in every normal daily situation / Ik zou in elke dagelijkse situatie in de autonome auto rijden** *
Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

15. **I would dare to drive with my regular car in the middle of Automated vehicles / Ik zou het durven om met mijn normale auto tussen de automatische voertuigen te rijden** *
Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

16. **I would be more comfortable in my car if Automated vehicles would be on a dedicated infrastructure, such as a seperated lane / Ik zou me meer op mijn gemak voelen in mijn auto wanneer Automatische Voertuigen op een daarvoor bestemde infrastructuur zouden rijden, zoals een aparte rijstrook** *
Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

17. **I enjoy driving my car / Ik vind het leuk om met mijn auto te rijden** *
Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

18. **Do you expect you will ever ride in a fully Automated vehicle as a common mode of transportation? / Denkt u dat u ooit in een volledig Autonome Auto zal rijden als allerdaags vervoersmiddel?** *
Markeer slechts één ovaal.

⬭ Yes / Ja
⬭ No / nee

19. **If yes, in what time frame do you expect to ride in a fully Automated vehicle as a common mode of transportation? / Zoja, binnen hoeveel jaar verwacht u in een volledig Autonome Auto te rijden als allerdaags vervoersmiddel?** *

Markeer slechts één ovaal.

- 0 - 5 year / jaar
- 5 - 10 year / jaar
- 10 - 15 year / jaar
- 15 - 20 year / jaar
- 20 - 25 year / jaar
- 25 - 30 year / jaar
- meer dan 30 year / jaar
- I never expect to drive in an Automated Vehicle / Ik verwacht nooit in een Autonome Auto te rijden

Thanks for participating and good luck with the experiment!

Post Experiment Survey Simulator Experiment Automated Vehicles

This survey should be conducted after participating in the Experiment
Deze enquête moet worden ingevuld nadat u deel heeft genomen aan het experiment.

*Vereist

1. **E-mailadres** *

____

Name or Reference Participant Number / Naam of Experiment Deelname referentie nummer

If you are willing to enter your name, or do not know your Reference Participant Number (yet) the data from this survey will be handled discrete, after coupling the experiment data with the survey data the name will be erased from the data set and will be made anonymous. If you are not willing to enter your name and do not know your Reference Participant Number please contact +31637332588.

Wanneer u zich (nog) niet bewust bent van uw Experiment Deelname Referentie Nummer en bereid bent u naam op te geven zal de data uit deze enquête discreet behandeld worden. Na het koppelen van uw gegevens aan de resultaten uit het simulator experiment zal uw naam verwijderd worden uit de data en zal de dataset geanonimiseerd worden. Wanneer u niet bereid bent u naam op te geven en u zich niet op de hoogte bent van uw Experiment Deelname Referentie Nummer kunt u contact opnemen met +31637332588.

2. **Name or Reference Participant Number / Naam of Experiment Deelname referentie nummer** *

____

3. **Did you experience any nausea during the experiment? / Heeft u zich op enig moment misselijk gevoeld tijdens het experiment?** *

Markeer slechts één ovaal.

- ◯ Yes / Ja
- ◯ No / Nee

4. **Did you experience general discomfort in any form during the experiment? / Heeft u zich op enig moment ongemakkelijk gevoeld tijdens het experiment in welke vorm dan ook?** *

Markeer slechts één ovaal.

- ◯ Yes / Ja
- ◯ No / Nee

5. **Did you experience stomach awareness during the experiment? / Heeft u uw maag gevoeld tijdens het experiment?** *

Markeer slechts één ovaal.

- ◯ Yes / Ja
- ◯ No / Nee

6. **Did you experience vertigo during the experiment? / Heeft u zich duizelig gevoeld tijdens het experiment?** *

Markeer slechts één ovaal.

- Yes / Ja
- No / Nee

Automated Vehicles/Autonome Voertuigen

Automated vehicles are vehicles that are able to drive on their own without any human imput. This vehicle is able to drive based on observations of the surroundings and information provided by other vehicles on the road and the infrastructure itself. / Autonome voertuigen zijn voertuigen die geheel zelfstandig kunnen rijden zonder menselijk ingrijpen. De auto kan zelf rijden op basis van het detecteren van zijn omgeving en informatie die hij krijgt van andere voertuigen op de weg en de infrastructuur zelf.

7. **I would only drive an Automated vehicle on less complicated infrastructure situations such as highways / Ik zou alleen in minder complexe situaties, zoals de snelweg, in de autonome auto rijden** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

8. **I am willing to drive an Automated vehicle in every normal daily situation / Ik zou in elke dagelijkse situatie in de autonome auto rijden** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

9. **I would dare to drive with my regular car in the middle of Automated vehicles / Ik zou het durven om met mijn normale auto tussen de automatische voertuigen te rijden** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

10. **I would be more comfortable in my car if Automated vehicles would be on a dedicated infrastructure, such as a seperated lane / Ik zou me meer op mijn gemak voelen in mijn auto wanneer Automatische Voertuigen op een daarvoor bestemde infrastructuur zouden rijden, zoals een aparte rijstrook** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens						Strongly agree / Helemaal mee eens

11. **I felt more comfortable when there was a barrier (gardrail) in between me and the Automated vehicle platoons than in the situation where the platoons where directly next to me? / Ik voelde me meer op mijn gemak toen er een barrière (Vangrail) tussen mij en de autonome auto platoons zat in vergelijking met de situaties waar de platoons direct naast mij reden? ***

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

12. **I felt on certain moments unsafe on the road during the experiment / Ik voelde me op een bepaald moment onveilig op de weg in het experiment ***

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

13. **If yes, in which situation? Can you elaborate on this? Zoja, in welke situatie? Kunt u dit verder toelichten?**

____

____

____

____

____

14. **I felt more safe when there was a guardrail between me and the platoons / Ik voelde me veiliger wanneer er een vangrail was tussen mij en de platoon ***

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

15. **In which of the following situation did you felt the most safe? / In welke van de volgende situatie voelde je je het veiligste? ***

Markeer slechts één ovaal.

⬭ When the platoons were seperated by a guardrail / Wanneer de platoons van mij gescheiden waren door middel van een vangrail

⬭ When the platoons were on a lane with a seperation by a continous line / Wanneer de platoons van mij gescheiden waren op een specifieke rijstrook met een doorgetrokken streep

⬭ When the platoons were on a lane with a seperation by a dashed line / Wanneer de platoons van mij gescheiden waren op een specifieke rijstrook met een onderbroken streep

16. **I have the feeling that the distance I keep to the car in front of me is appropriate / Ik heb het gevoel dat de afstand die ik houd tot de auto voor me voldoende is** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

17. **I have the feeling that the distance I keep to the car in front of me is shorter than usual because of the platoons next to me/ Ik heb het gevoel dat de afstand die ik houd tot de auto voor me korter is wanneer er platoons naast me rijden dan normaal** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

18. **I have the feeling that the distance I keep to the car in front of me is longer than usual because of the platoons next to me/ Ik heb het gevoel dat de afstand die ik houd tot de auto voor me langer is wanneer er platoons naast me rijden dan normaal** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

19. **I enjoyed participating in this experiment / Ik vond het leuk om deel te nemen aan dit experiment** *

Markeer slechts één ovaal.

	1	2	3	4	5	
Strongly disagree / Helemaal niet mee eens	⬭	⬭	⬭	⬭	⬭	Strongly agree / Helemaal mee eens

20. **Do you have any other remarks? / Heeft u nog opmerkingen?**

Thank you for your participation / Bedankt voor je deelname

C. Order of the scenarios in the driving simulator

P1	Baseline	CAL	LABL	LAL
P2	Baseline	LABL	CAL	LAL
P3	Baseline	LAL	LABL	CAL
P4	CAL	Baseline	LABL	LAL
P5	CAL	LABL	Baseline	LAL
P6	CAL	LAL	LABL	Baseline
P7	LABL	LAL	Baseline	CAL
P8	LABL	Baseline	LAL	CAL
P9	LABL	CAL	Baseline	LAL
P10	LAL	Baseline	LABL	CAL
P11	LAL	LABL	Baseline	CAL
P12	LAL	CAL	LABL	Baseline
Px	…	…	…	…

D. Informed consent document

Research Title: *Automated vehicles and infrastructure design*

Responsible researcher: Mathijs Schoenmakers

To fill in by the participant

I hereby declare that I am well informed about the ground, method and goal of this research and that I trust that my data will be handled discrete. I know that my data will be made anonymously and it will not be passed on to other uninvolved parties besides Delft University of Technology, Eindhoven University of Technology, Rijkswaterstaat and the involved researchers.

I am aware that my driving behavior will be tracked in the driving simulator and that this only will be used for analysis purposes. The data that will be gathered in this research will only be used for analysis and scientific purposes.

I am aware of the fact that there is a possibility that I might experience some discomfort after and/or during the experiment. I am aware that driving simulator sickness might occur in some cases.

I am taking part in this research study voluntary and I am well informed about this research.

Date:

Location: Delft, the Netherlands

Name of researcher

Mathijs Schoenmakers

Signature

Name of participant

Signature

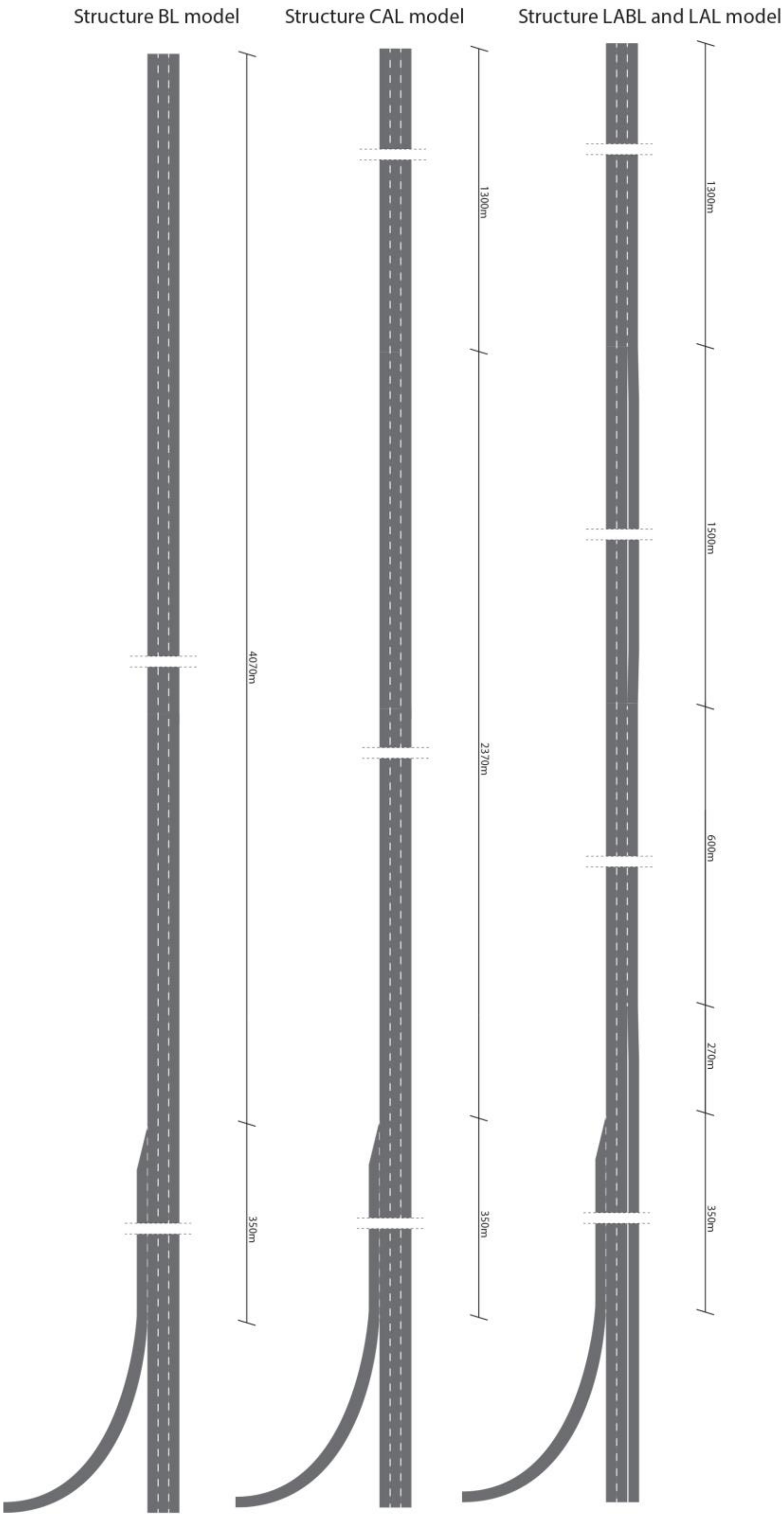
E. Receipt of Money

I hereby declare that I have received my monetary compensation for participating in the driving simulator experiment of Mathijs Schoenmakers at Delft University of Technology. This research is conducted on behalf of Delft University of Technology, Eindhoven University of Technology and Rijkswaterstaat.

I acknowledge the receipt cash payment of € 10.00 (ten euros) on _____________ after participating in the experiment from Mathijs Schoenmakers at Delft University of Technology.

Date:	Location: Delft, the Netherlands
Name of researcher	Name of participant
Mathijs Schoenmakers	
Signature	Signature

F. The structure of the models developed in VISSIM

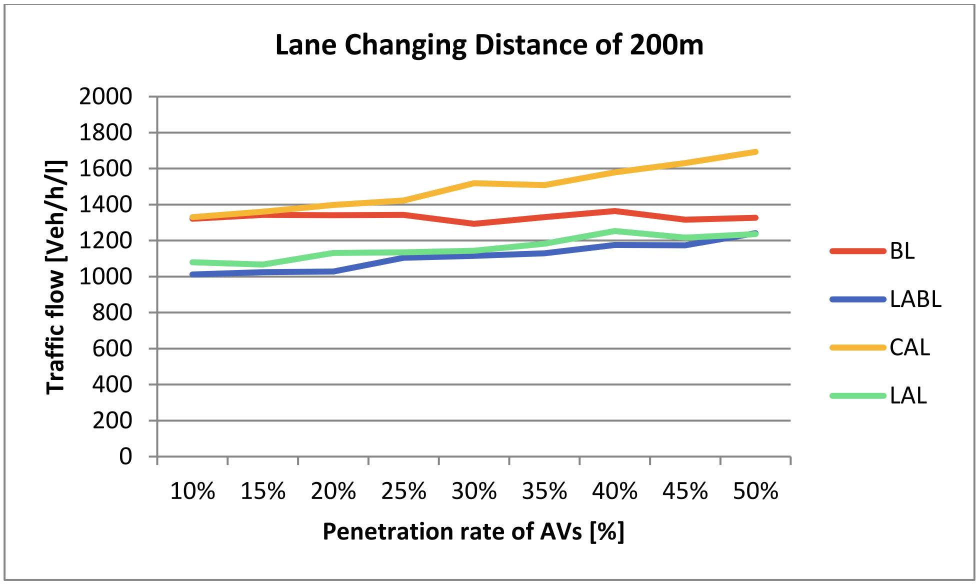


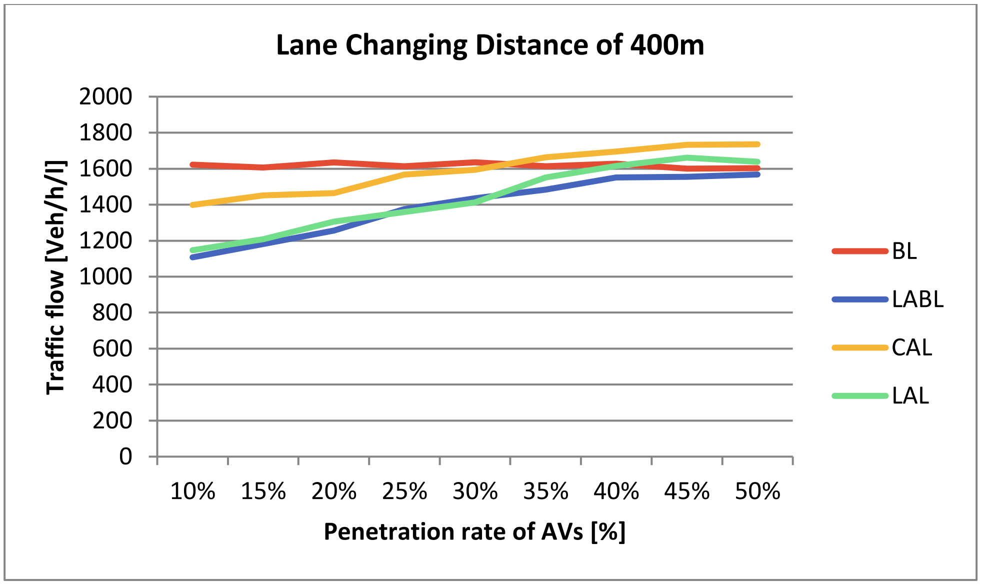
G. Overview of all the models that were ran in VISSIM

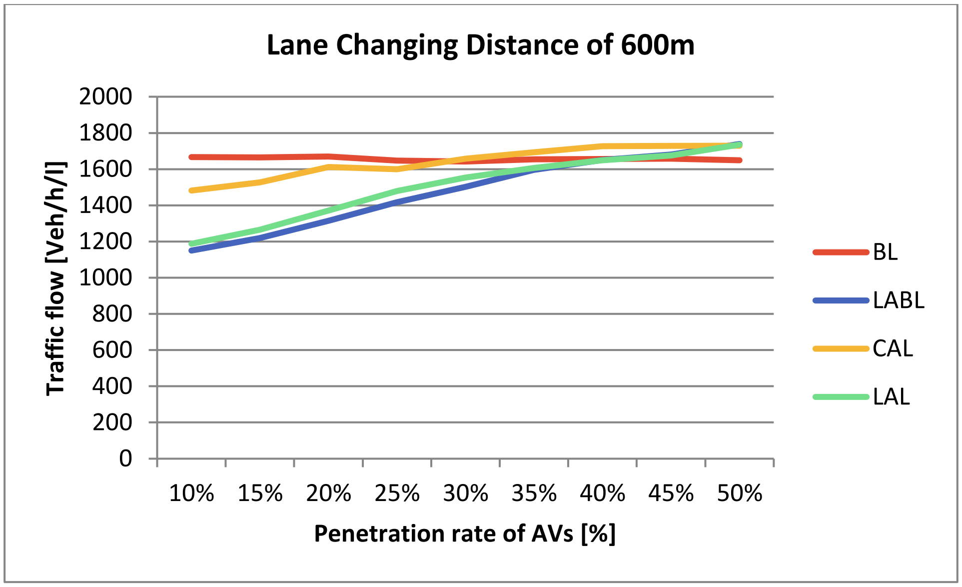
scenario	Design of the dedicated lane scenarios	Vehicle input	Penetration rate	Weaving section length	Lane change distance
1	BL, CAL, LABL, LAL	5500	10% - 50%	600	800
2	BL, CAL, LABL, LAL	5000	10% - 50%	600	800
3	BL, CAL, LABL, LAL	5500	10% - 50%	800	800
4	BL, CAL, LABL, LAL	5000	10% - 50%	800	800
5	BL, CAL, LABL, LAL	5500	10% - 50%	1000	800
6	BL, CAL, LABL, LAL	5000	10% - 50%	1000	800
7	BL, CAL, LABL, LAL	5500	10% - 50%	600	200
8	BL, CAL, LABL, LAL	5000	10% - 50%	600	200
9	BL, CAL, LABL, LAL	5500	10% - 50%	600	400
10	BL, CAL, LABL, LAL	5000	10% - 50%	600	400
11	BL, CAL, LABL, LAL	5500	10% - 50%	600	600
12	BL, CAL, LABL, LAL	5000	10% - 50%	600	600
13	BL, CAL, LABL, LAL	5500	10% - 50%	600	800
14	BL, CAL, LABL, LAL	5000	10% - 50%	600	800
15	BL, CAL, LABL, LAL	5500	10% - 50%	600	1000
16	BL, CAL, LABL, LAL	5000	10% - 50%	600	1000

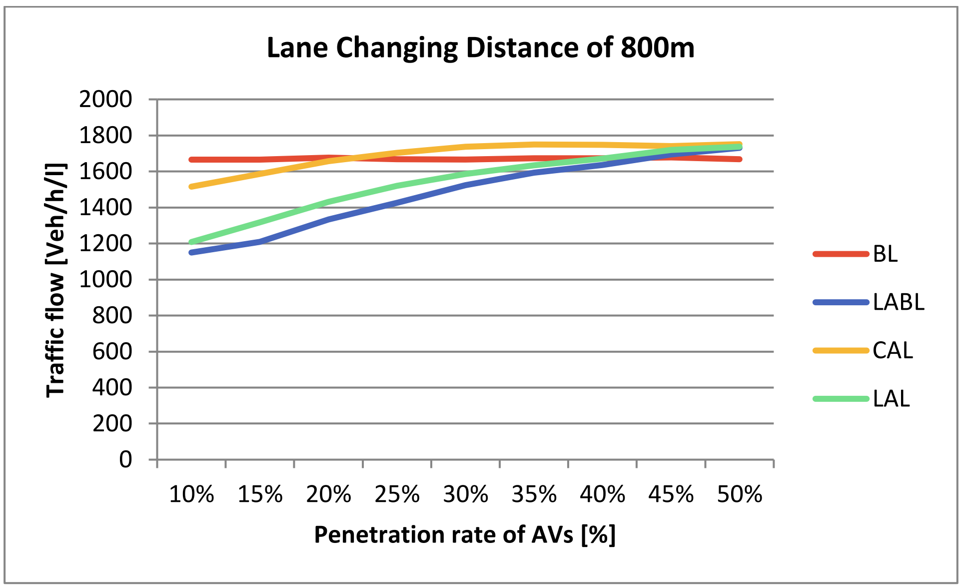
H. Output graphs of VISSIM

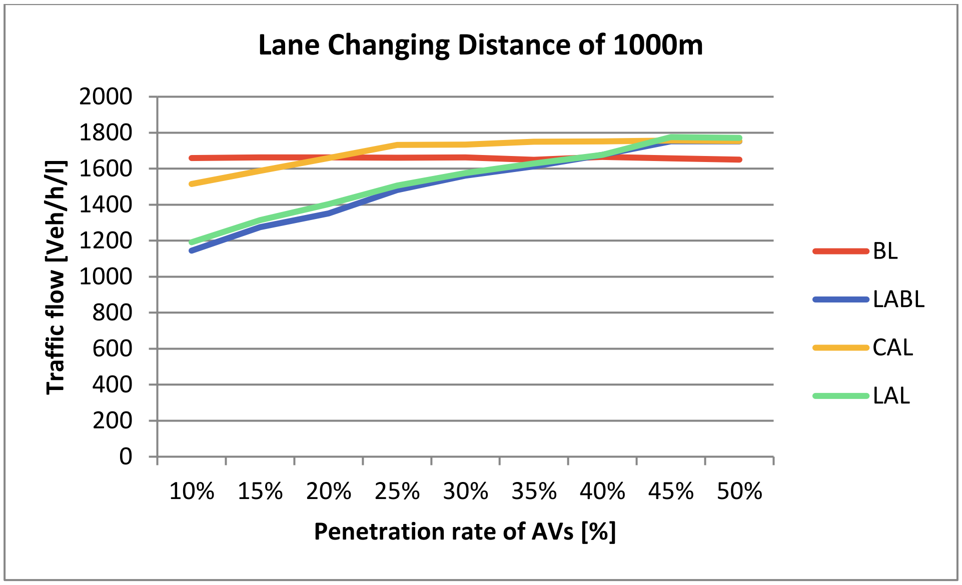
Traffic flow intensity graphs with a Vehicle input of 5500 and increasing decision mode 200-1200 in steps of 200

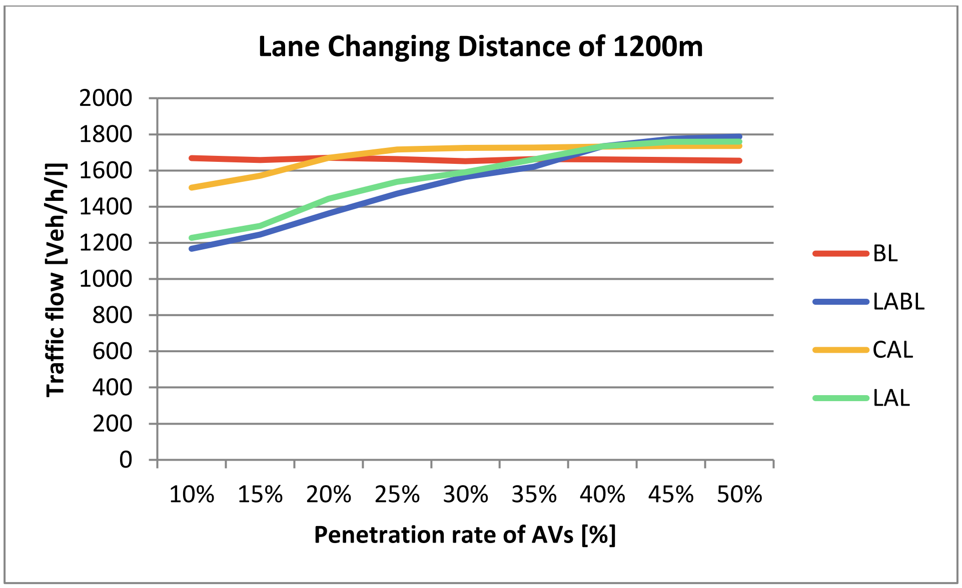




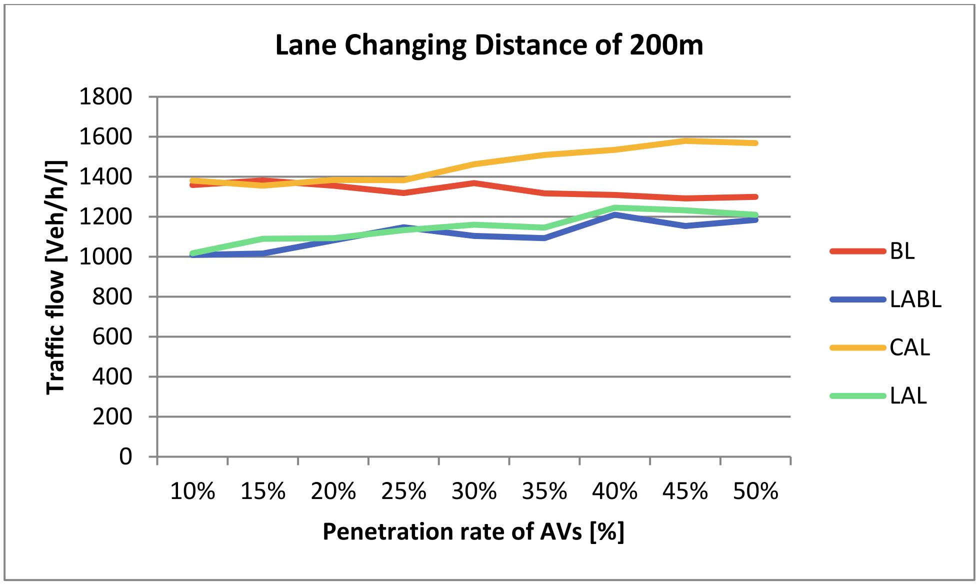

Lane Changing Distance of 600m
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Traffic flow [Veh/h/l]
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

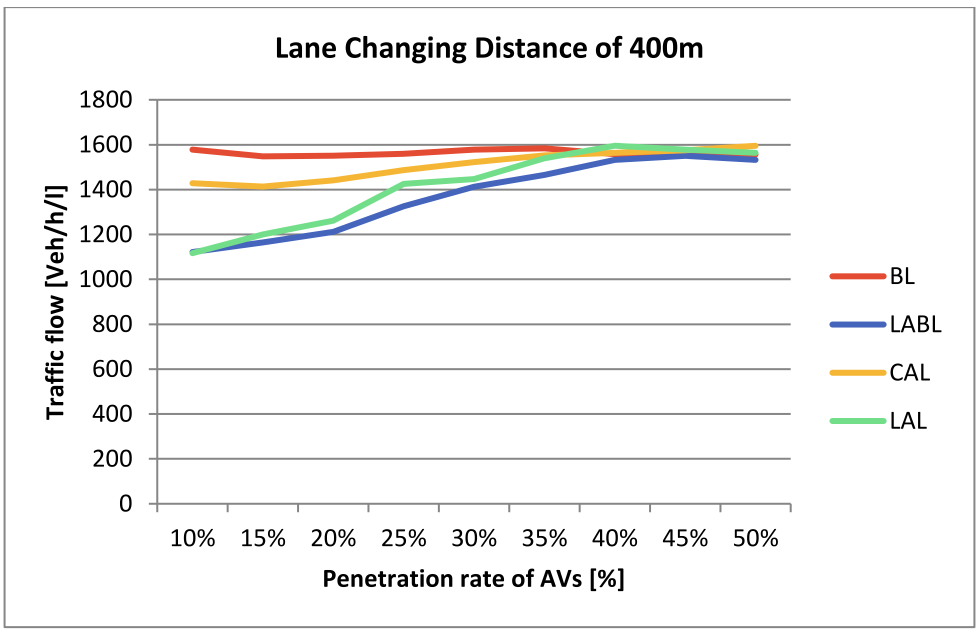

Lane Changing Distance of 800m
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Traffic flow [Veh/h/l]
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

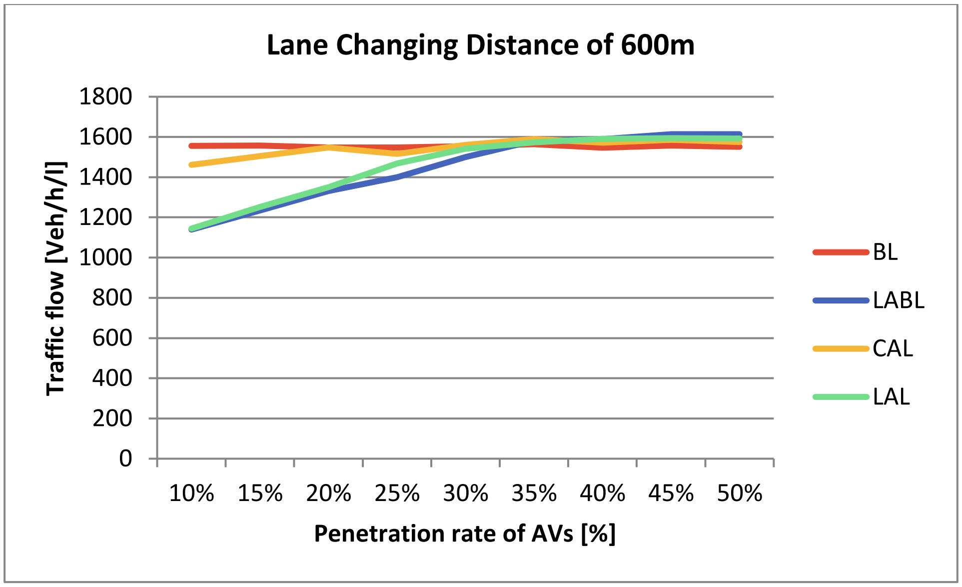

Lane Changing Distance of 1000m
Traffic flow [Veh/h/l]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

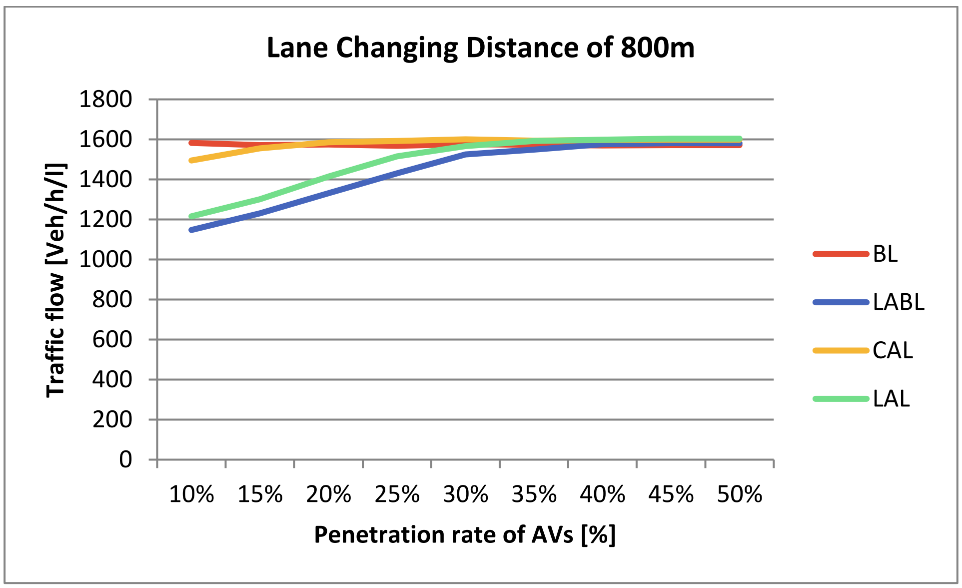

Lane Changing Distance of 1200m
Traffic flow [Veh/h/l]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

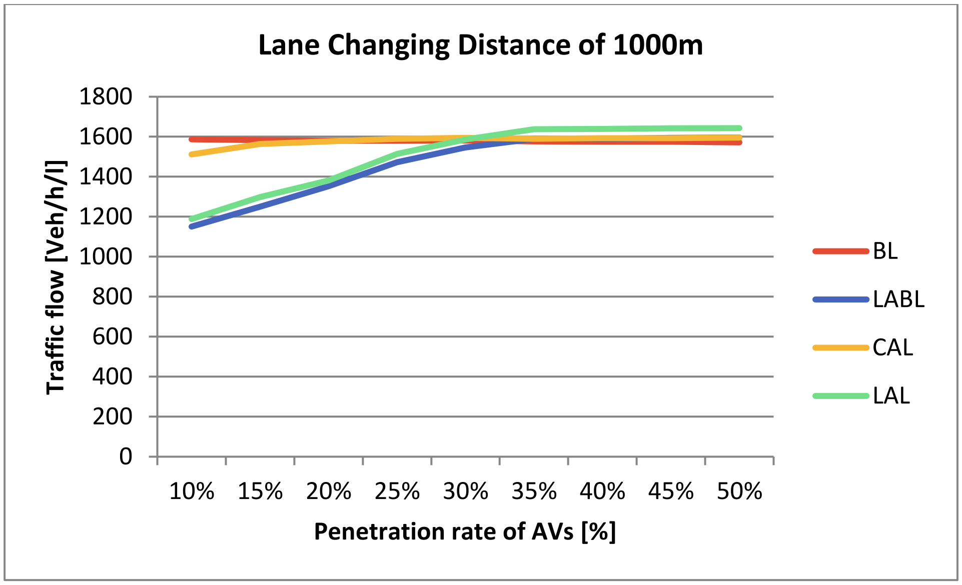
Traffic flow intensity graphs with a Vehicle input of 5000 and increasing decision mode 200-1200 in steps of 200

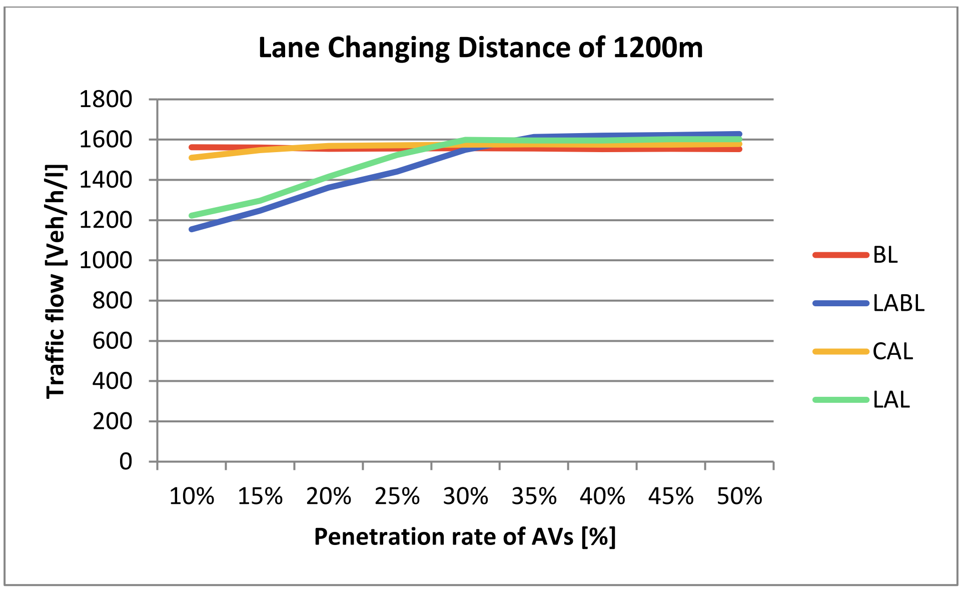




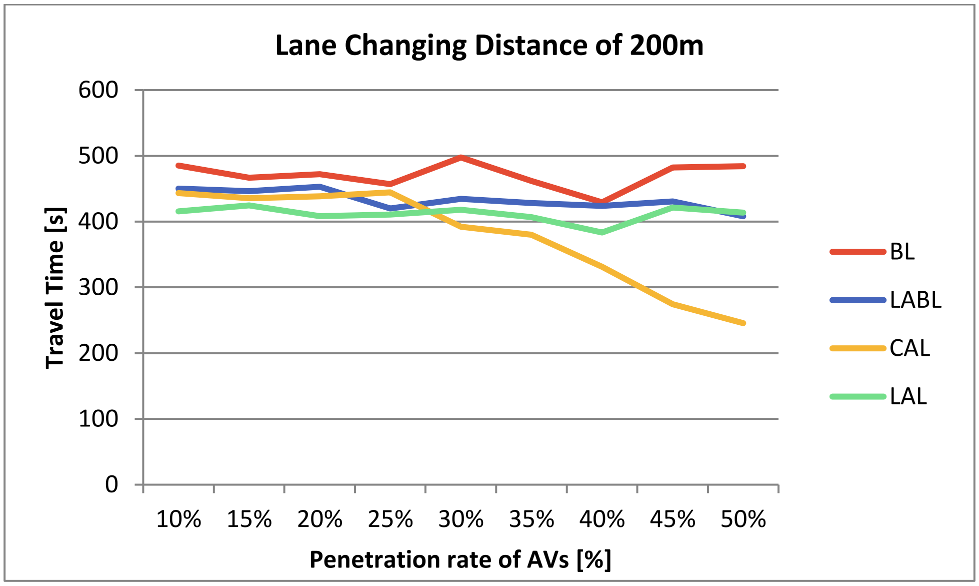

Lane Changing Distance of 600m
Traffic flow [Veh/h/l]
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

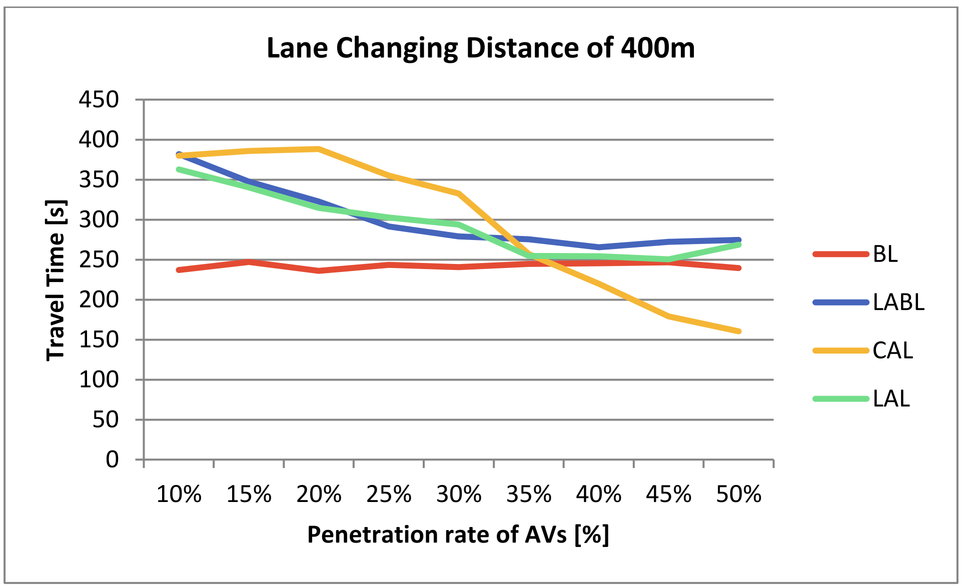

Lane Changing Distance of 800m
Traffic flow [Veh/h/l]
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

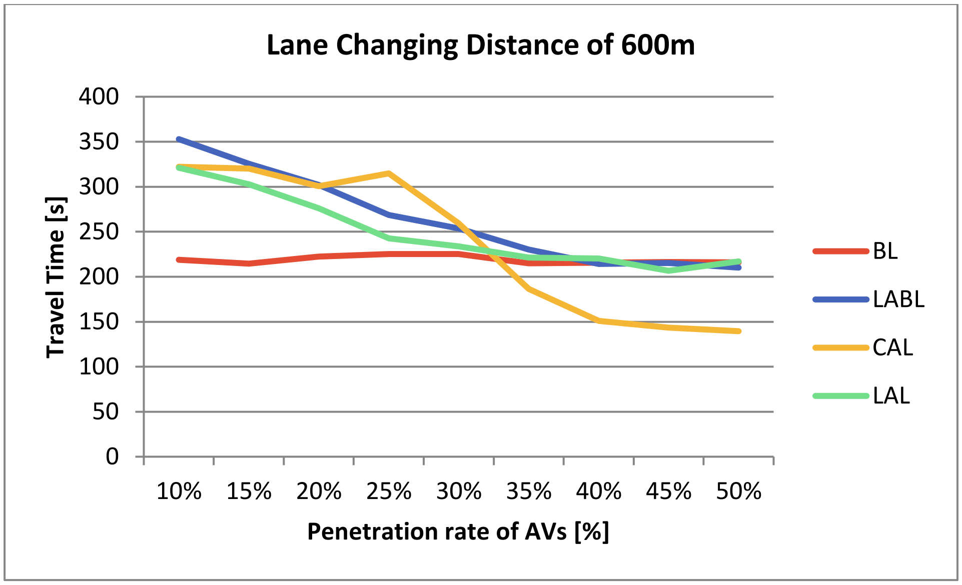

Lane Changing Distance of 1000m
Traffic flow [Veh/h/l]
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

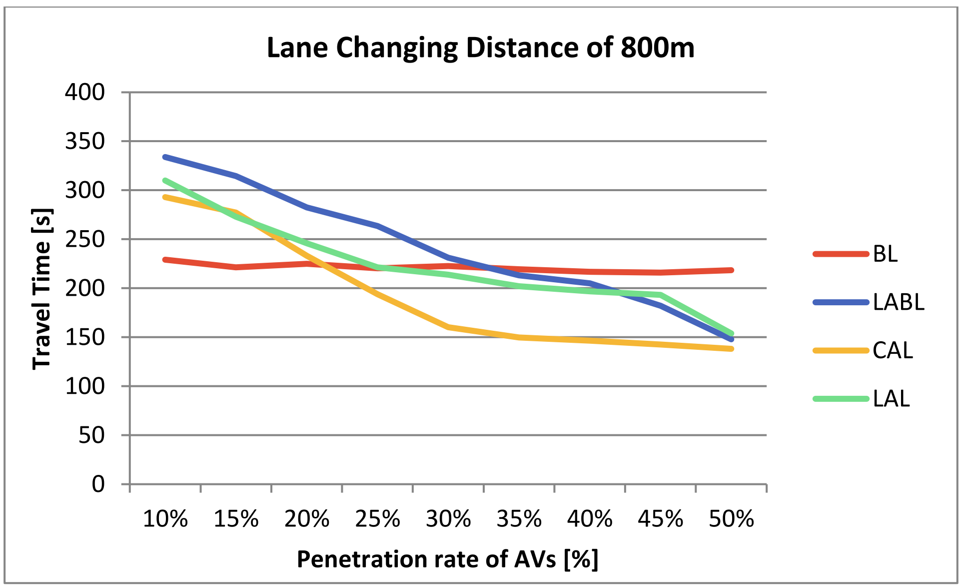

Lane Changing Distance of 1200m
Traffic flow [Veh/h/l]
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

Travel Time graphs with a Vehicle input of 5500 and increasing decision mode 200-1200 in steps of 200






Lane Changing Distance of 600m
Travel Time [s]
400
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL


Lane Changing Distance of 800m
Travel Time [s]
400
350
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10%
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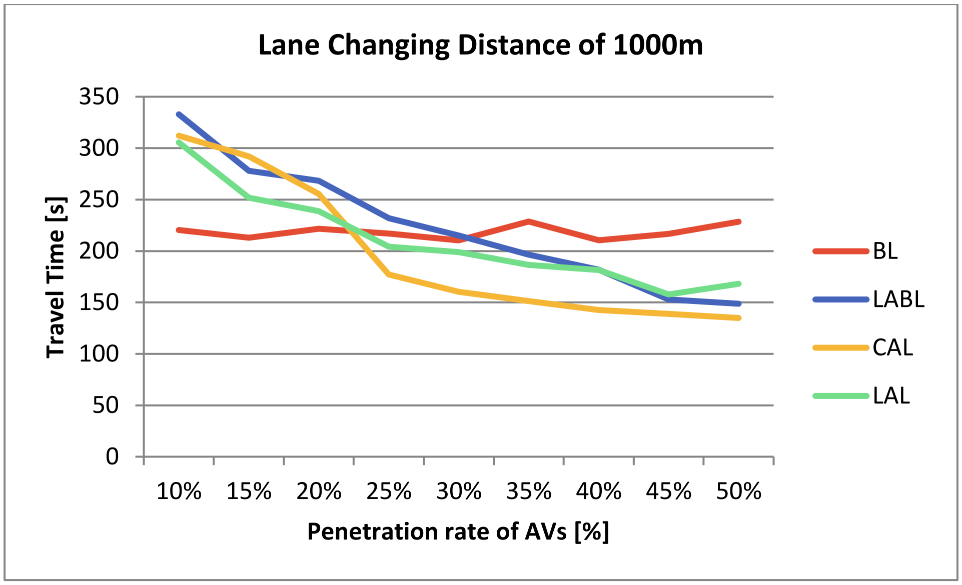
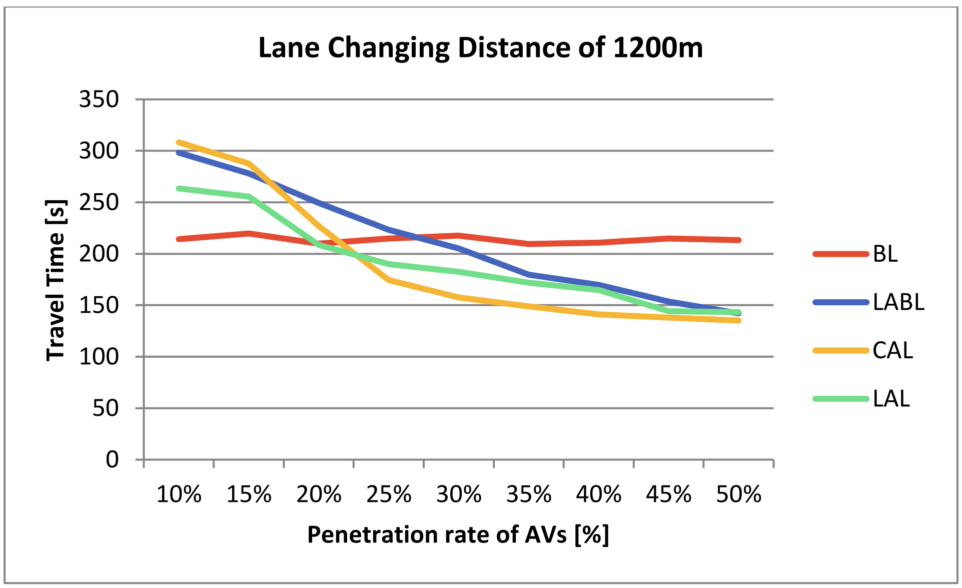
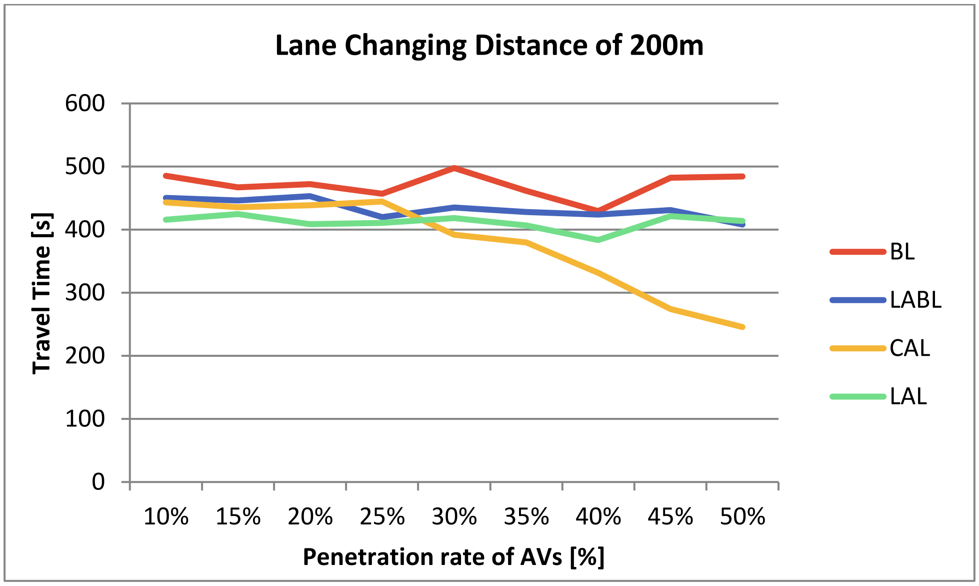
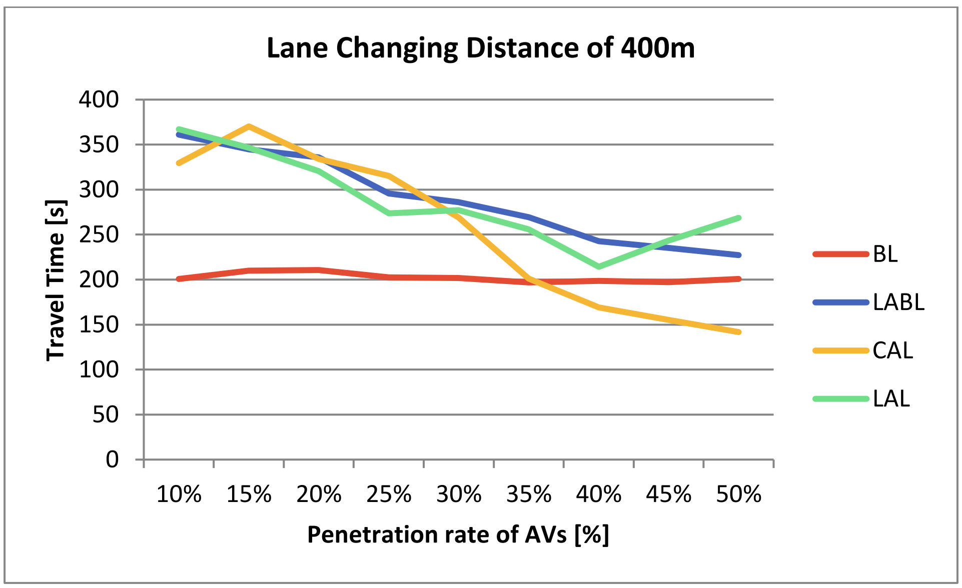
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

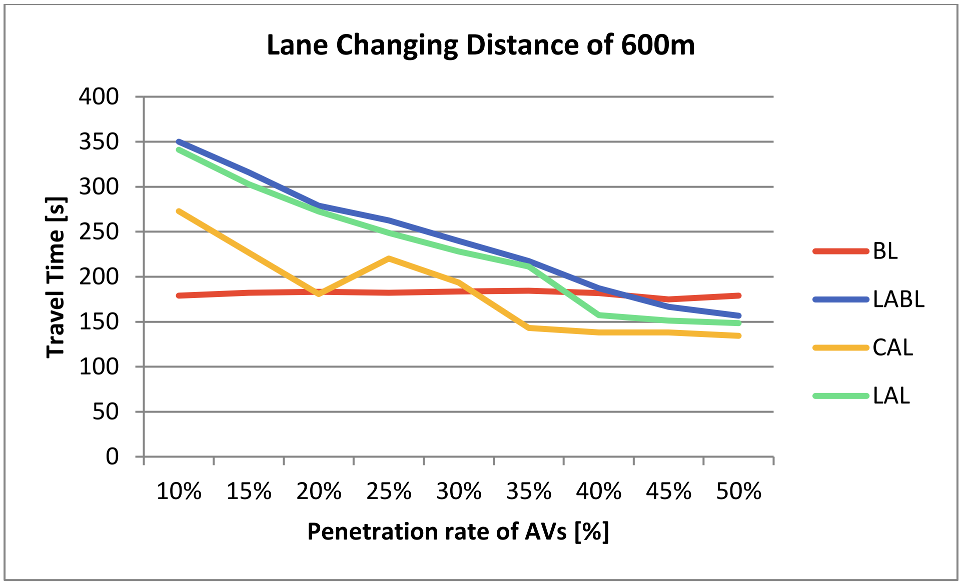

Lane Changing Distance of 1000m
350
300
250
200
150
100
50
0
Travel Time [s]
10% 15% 20% 25% 30% 35% 40% 45% 50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

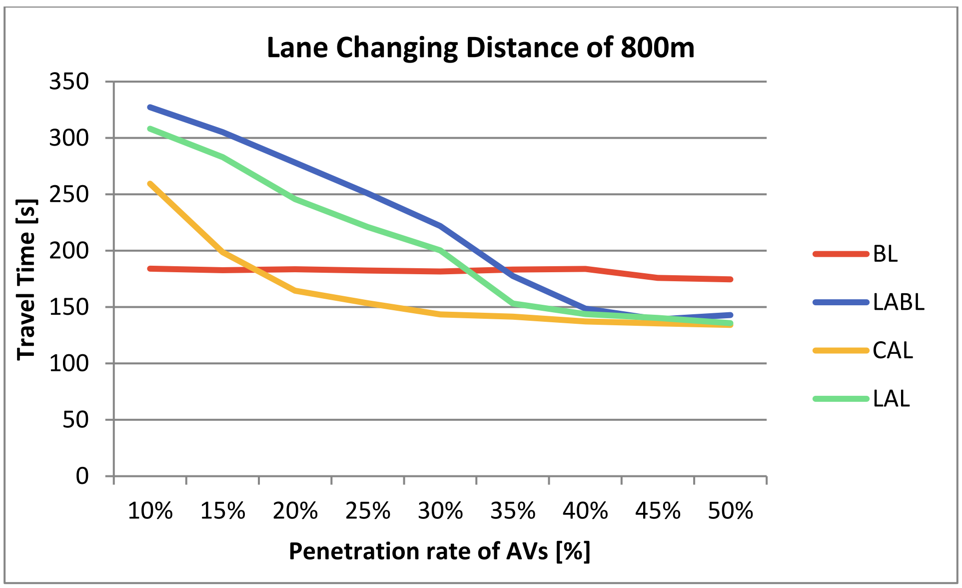

Lane Changing Distance of 1200m
350
300
250
200
150
100
50
0
Travel Time [s]
10% 15% 20% 25% 30% 35% 40% 45% 50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

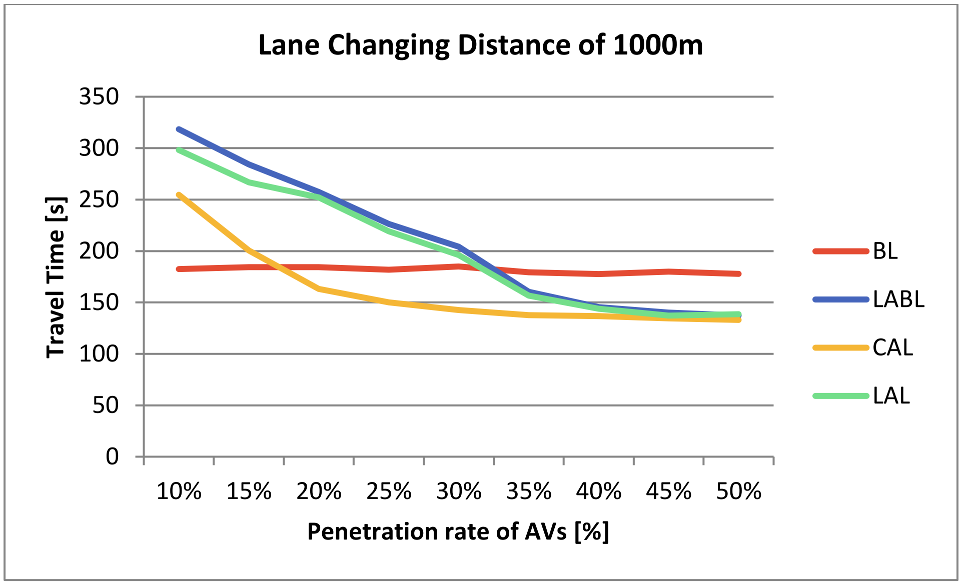
Travel time graphs with a vehicle input of 5000 and increasing decision mode 200-1200 in steps of 200

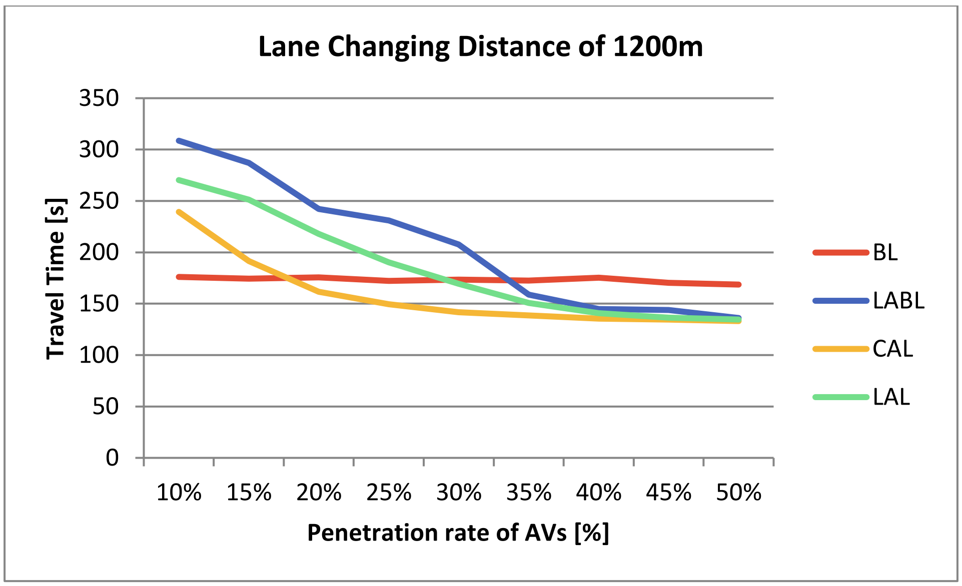




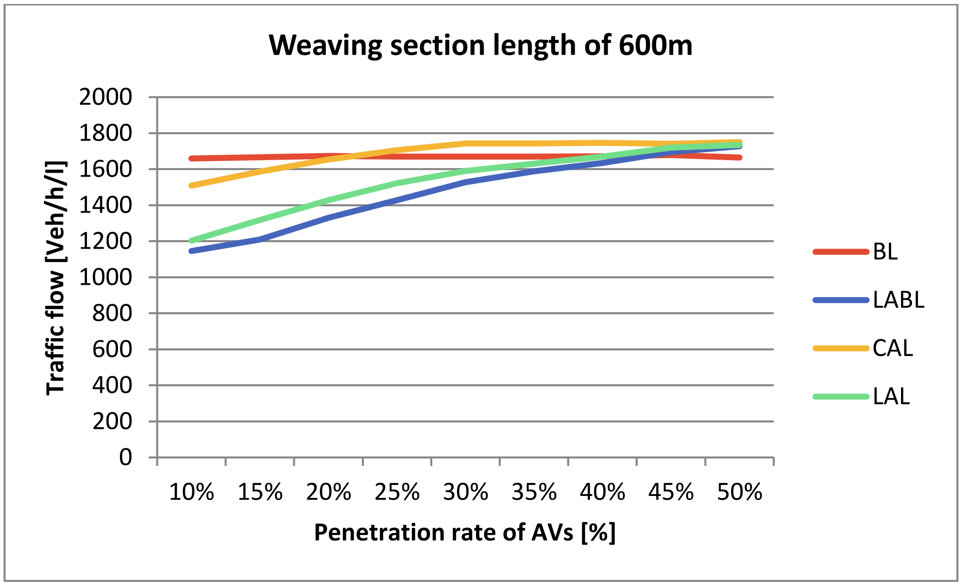

Lane Changing Distance of 600m
Travel Time [s]
400
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

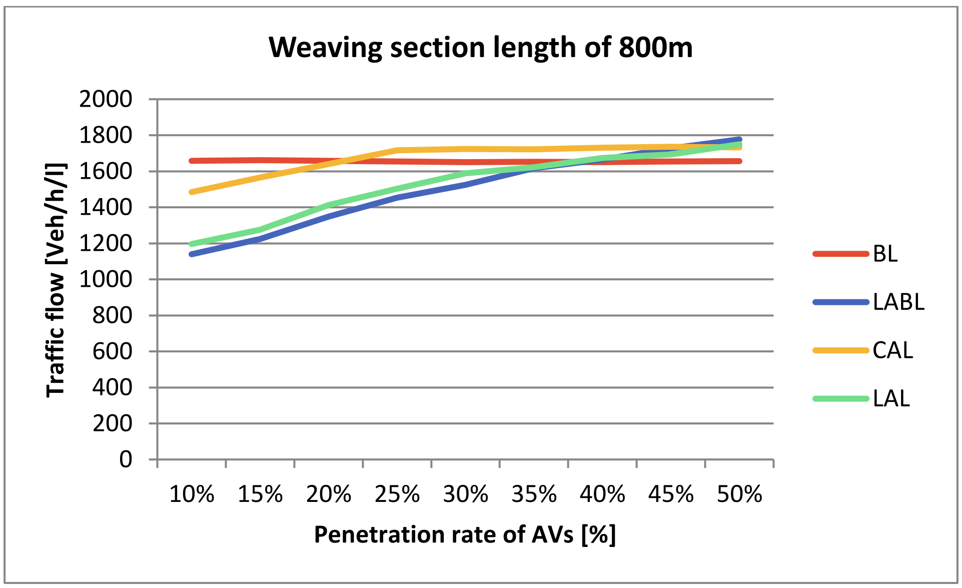

Lane Changing Distance of 800m
Travel Time [s]
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

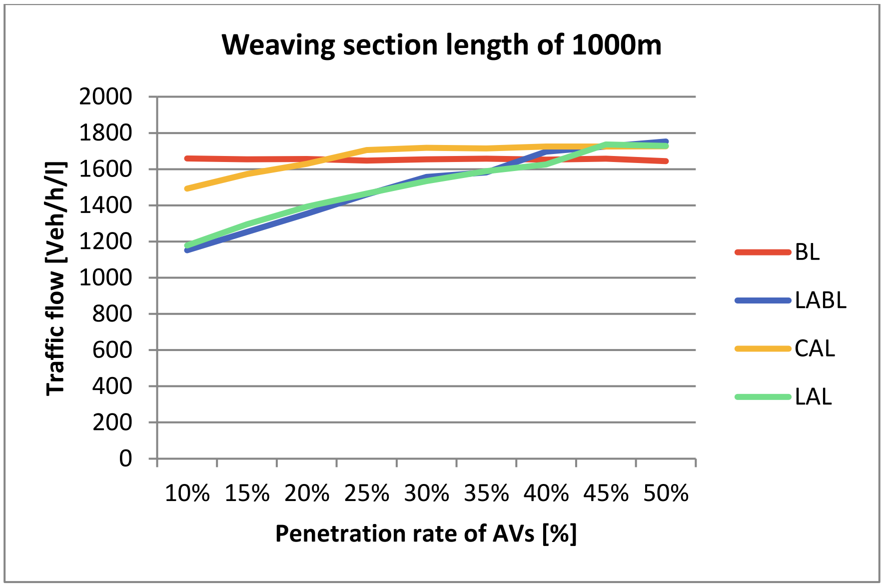

Lane Changing Distance of 1000m
Travel Time [s]
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL


Lane Changing Distance of 1200m
Travel Time [s]
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

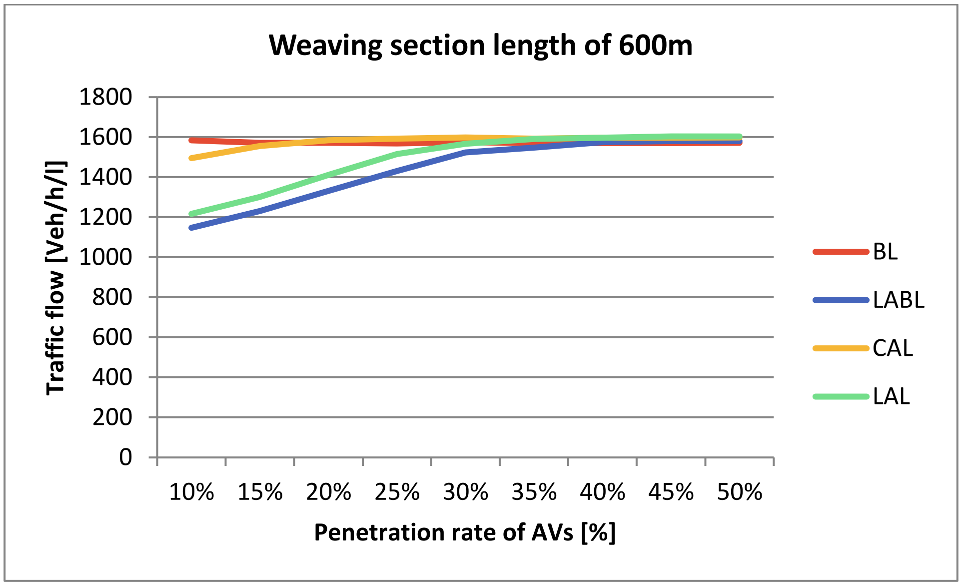
Traffic flow graphs with a vehicle input of 5500 and weaving length sections of 600-800 and 1000 m

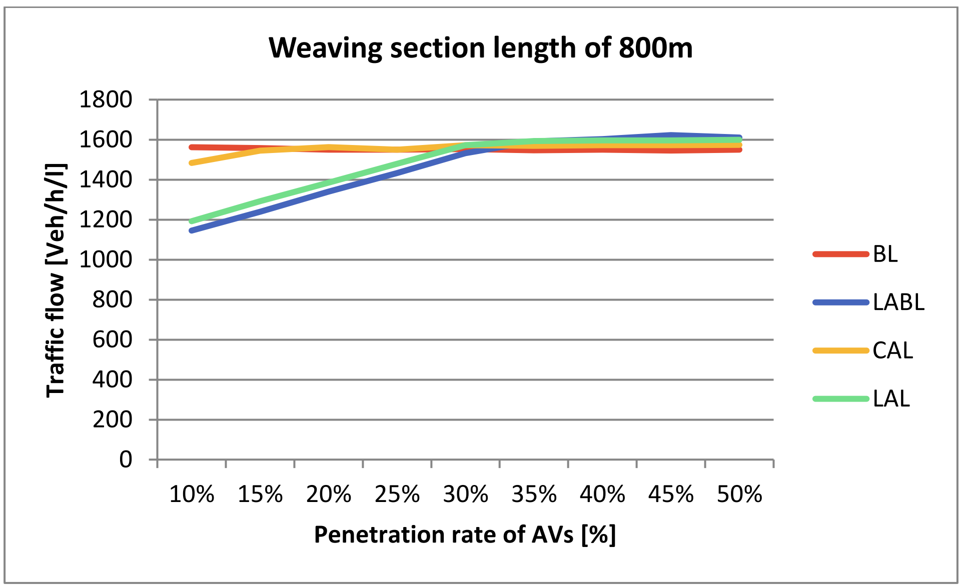


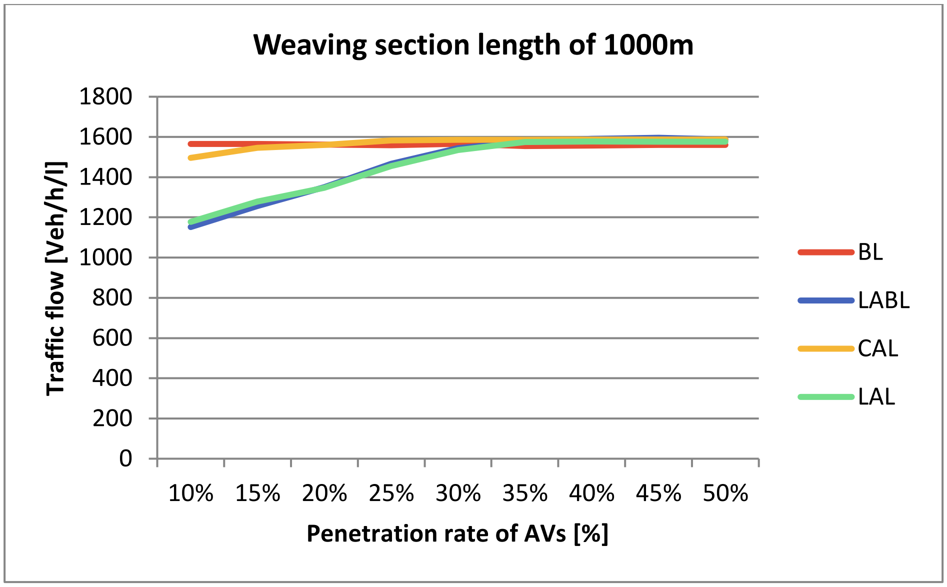



Weaving section length of 1000m
Traffic flow [Veh/h/l]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

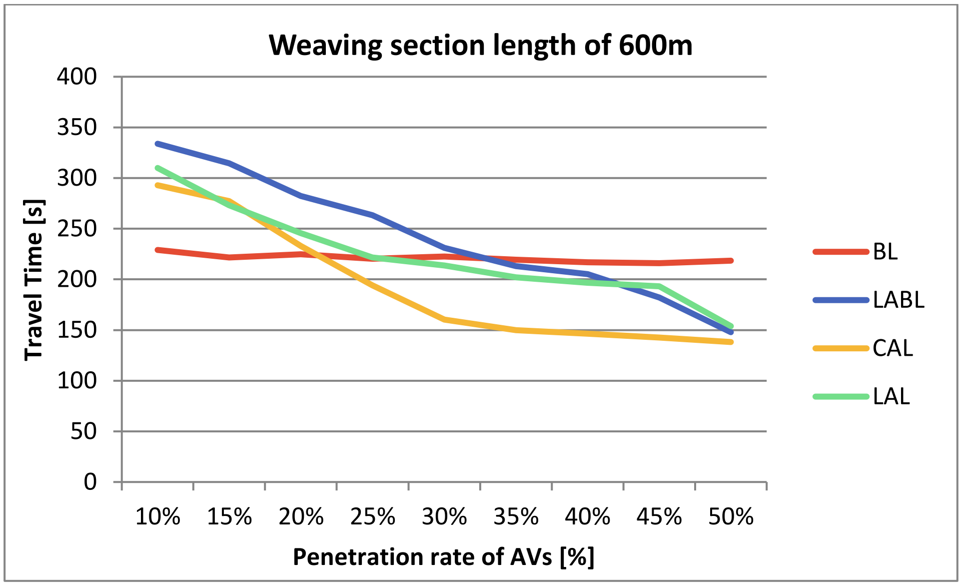
Traffic flow graphs with a vehicle input of 5000 and weaving length sections of 600-800 and 1000 m

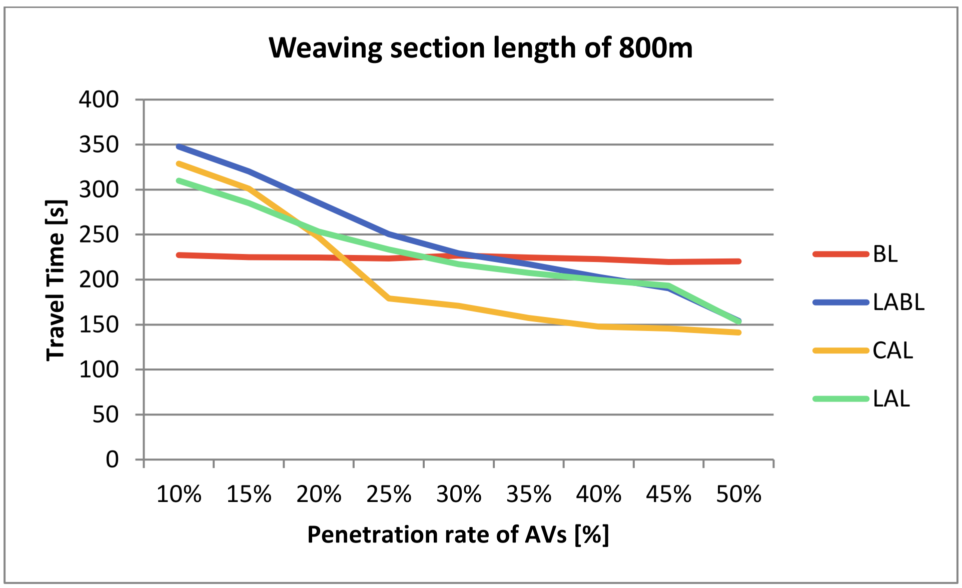


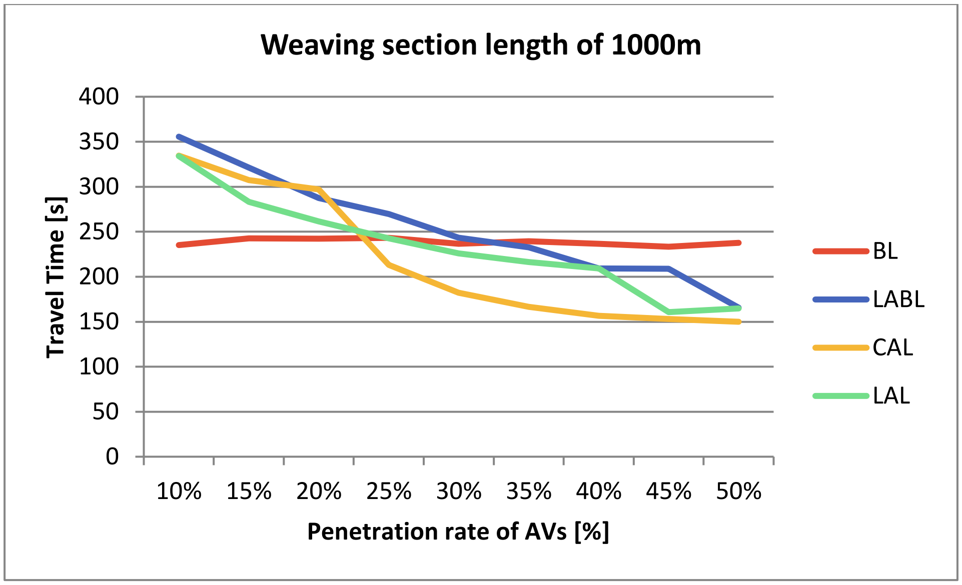



Weaving section length of 1000m
Traffic flow [Veh/h/l]
1800
1600
1400
1200
1000
800
600
400
200
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

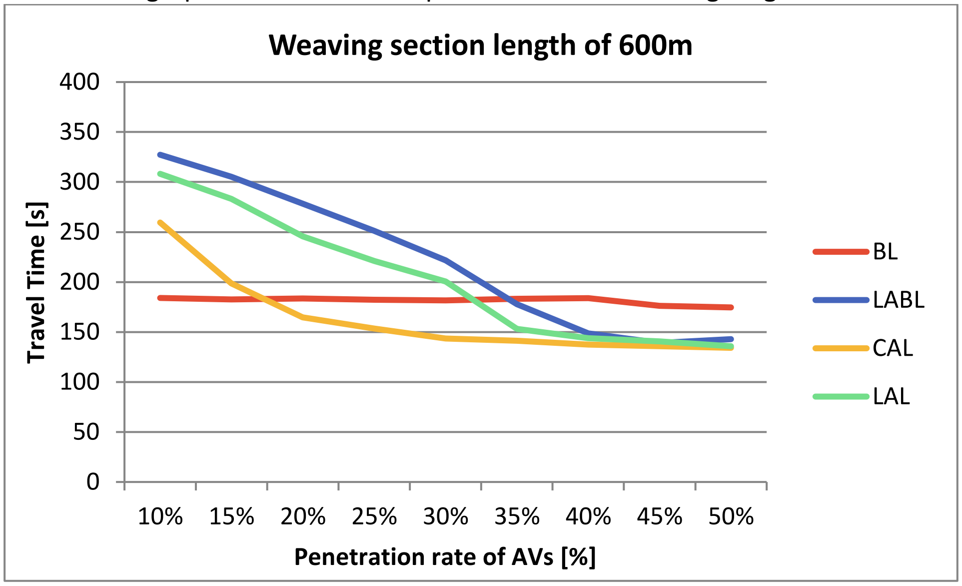
Travel time graphs with a vehicle input of 5500 and weaving length sections of 600-800 and 1000 m

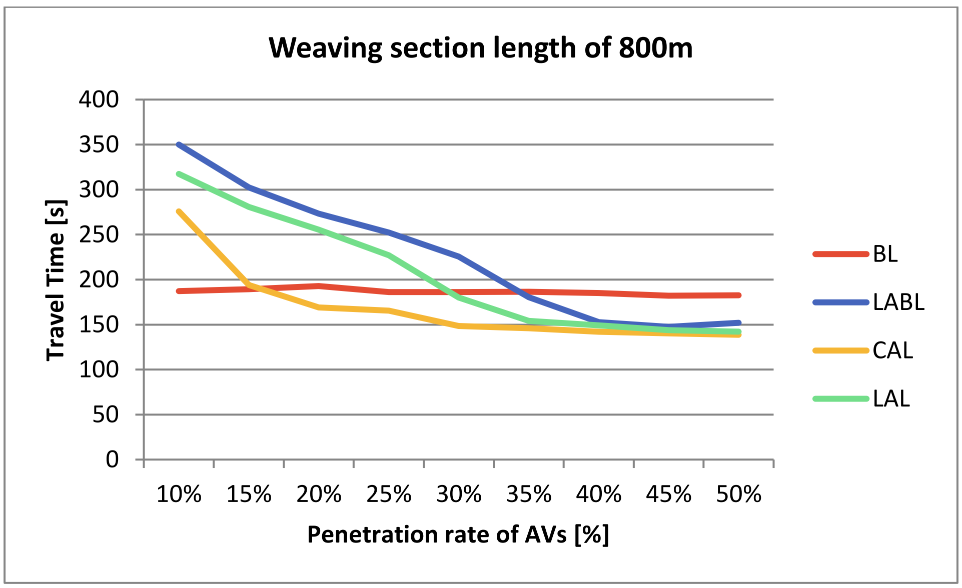


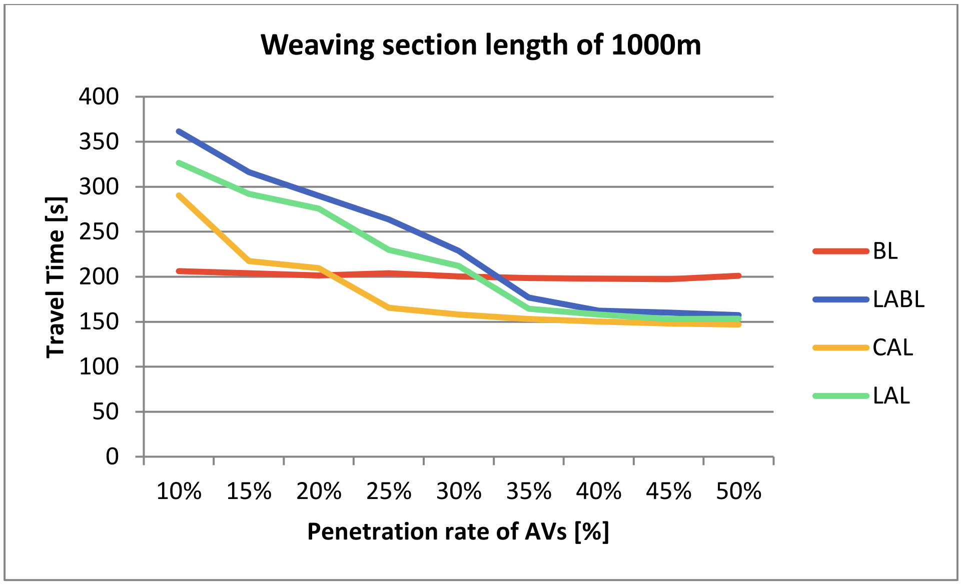



Weaving section length of 1000m
Travel Time [s]
400
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

Travel time graphs with a vehicle input of 5000 and weaving length sections of 600-800 and 1000 m






Weaving section length of 1000m
Travel Time [s]
400
350
300
250
200
150
100
50
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
Penetration rate of AVs [%]
BL
LABL
CAL
LAL

I. Statements about safety participants made in the driving simulator experiment

Did you feel unsafe on a certain moment, if yes, elaborate:

- De overgang van met barrier naar zonder barrier was in eerste instantie even schrikken
- Als er een groep auto's lange tijd naast me bleef rijden. Sowieso is het niet heel prettig als er een auto naast je blijft rijden
- Hmm, niet heel onveilig, maar in de situatie met de doorbroken wegmarkering is het niet heel prettig als je door zo'n auto wordt ingehaald.
- In de eerste situatie, dus met de zelfrijdende voertuigen zonder bariere of doorgetrokken streep, voelde ik mij onveiliger, zeker met inhalen.
- Als er 4 auto's dicht op elkaar je links inhalen, met klein snelheidsverschil. Lijkt een soort vrachtwagen op die manier

J. Software tools used

Here is an overview of the tools used.

Objective	Tool	format
Developing road design models	Sketchup Pro	.skp exported as .fbx
Developing Driving Simulator Models	Unity	.exe
Tracking data in simulator	.json script	.json
Exporting data from json to csv		
Processing data	Excel	.csv converted to .xls
Analyzing data	SPSS	.spss
Developing traffic flow models	VISSIM	.inpx
Processing output VISSIM		