Design and Evaluation of Dedicated Lanes for Connected and Automated Vehicles

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Solmaz Razmi Rad

Delft University of Technology

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Design and Evaluation of Dedicated Lanes for Connected and Automated Vehicles

Dissertation

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by the authority of the Rector Magnificus prof.dr.ir. T.H.J.J. van der Hagen

to be defended publicly on

Monday 20 March 2023 at 10:00 o'clock

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In memory of my father,

Hosein.

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Chapter 1

Introduction

Connected and automated vehicles (CAVs) are the next generation of vehicles that are expected to become commercially available in the next decades (Milakis et al., 2015; Nieuwenhuijsen et al., 2018). Depending on their level of automation, they are able to take over some or all of the driving tasks from human drivers and therefore are expected to improve traffic safety by reducing or eliminating the role of human driver (Fagnant and Kockelman, 2015). Also, they could potentially enhance the traffic efficiency by driving with short time headways (THWs). CAVs can also have positive implications on air quality by reducing fuel consumption (Ivanchev et al., 2017; Lu & Shladover, 2014).

The market penetration rate (MPR) of CAVs is expected to develop gradually in the near future (Bansal and Kockelman, 2017). Therefore, during the transition to full automation, CAVs are likely to share the road with other vehicles that are driven manually by human drivers. A key concern in this respect is that knowledge about the interactions between manual vehicles (MVs) and CAVs in mixed traffic is largely lacking. Human drivers might behave and interact with CAVs differently than with MVs. These interactions, and the potential behavioural adaptations of human drivers, can affect traffic efficiency and traffic safety either positively or negatively.

Dedicating one lane of a motorway exclusively to CAVs is an alternative scenario for the deployment of CAVs. It decreases the interactions between CAVs and MVs and thus *possibly* enhances safety and by concentrating CAV's on a lane it could improve traffic flow operations. However, knowledge on the design and operation of dedicated lanes (DL) and their impacts on the behaviour of CAV and MV drivers is lacking in the literature. Therefore, this thesis will investigate the following two questions:

(1) What are the underlying factors in design and operation of DLs and what are the relations between these factors?

(2) What is the impact of a DL on the behaviour of CAV and MV drivers?

Answering these two research questions is critical for decision making on how to accommodate CAVs on our road network.

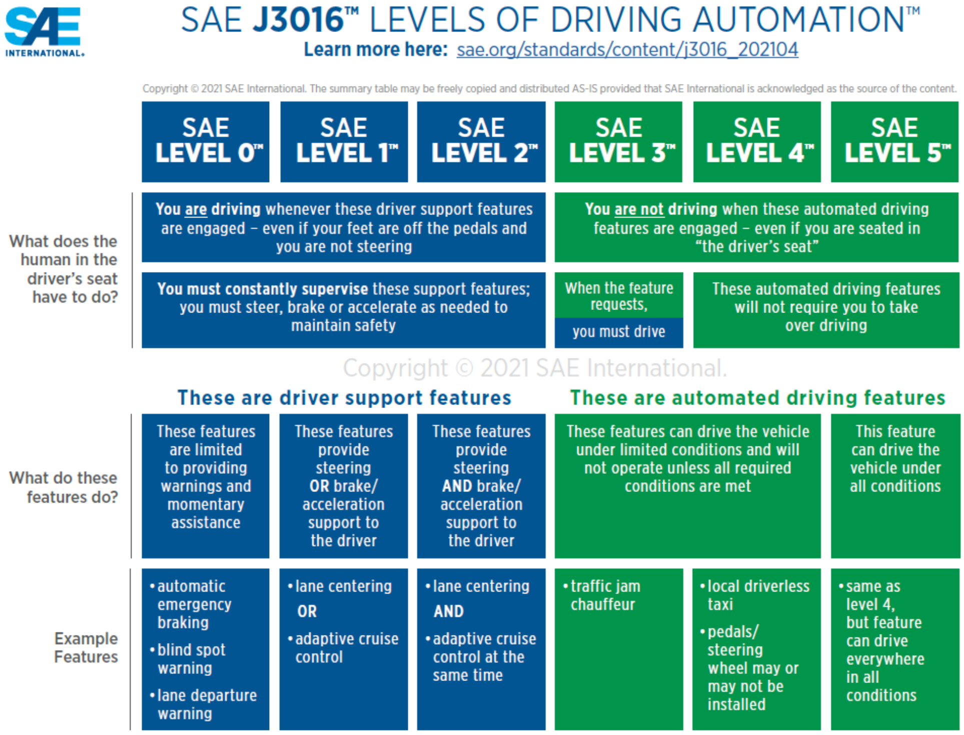
This thesis, firstly identifies the factors that could affect the safety and efficiency of DLs on motorways, taking into account human factors, design and utilization policies of DLs, and the MPR of CAVs; secondly, investigates the behaviour of drivers of CAVs and MVs in mixed traffic and compares that to the situation when CAVs are separated by utilizing a DL.

This introductory chapter is structured as follows. First the research background is introduced (Section 1.1), followed by the presentation of the problem statement (Section 1.2), and the research objectives, research questions and the scope of this thesis (Section 1.3). Section 1.4 describes the research approach and the designed empirical studies to address the research questions. The main scientific and practical contributions are discussed in Section 1.5. Finally, Section 1.6 outlines the contents of this dissertation.

1.1 Background

Traffic congestion and accidents cause a serious challenge to the users and operators of the road traffic system. The World Health Organization has identified traffic accidents as one of the leading causes of deaths and injuries (WHO, 2019). The societal costs of road accidents are estimated at 17 billion euro, only in the Netherlands in 2018, equivalent to more than 2% of the gross domestic product (GDP) (SWOV, 2020). According to the National Highway Traffic Safety Administration (NHTSA), human error is a contributing factor to about 94% of motor vehicle accidents (NHTSA, 2016). By reducing/eliminating the role of the human driver, automated driving is expected to eliminate accidents in which the human error is a major contributing factor. Moreover, automated driving has the potential to improve traffic flow efficiency by increasing capacity and traffic stability (Park et al., 2021; Vranken and Schreckenberg, 2022; Hoogendoorn et al., 2014).

The Society of Automotive Engineers (SAE) identifies six levels of automation which are demonstrated in Figure 1-1 (SAE International, 2021).



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	SAE LEVEL 0™	SAE LEVEL 1™	SAE LEVEL 2™	SAE LEVEL 3™	SAE LEVEL 4™	SAE LEVEL 5™
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 1-1 Levels of vehicle automation (SAE International, 2021).

At level 0 (No Driving Automation), the driver is responsible for all the dynamic driving tasks (DDT). At level 1 (Driver Assistance), either the longitudinal or the lateral movement is controlled by the driver. At level 2 (Partial Driving Automation) the system takes over longitudinal and lateral control, but the driver is responsible to permanently monitor the system and is expected to be ready to resume control at any time. According to SAE, the driver is in fact *driving* when the driver support features (levels 0-2) are engaged, while with automated driving features (levels 3-5) the driver is *not driving* anymore and the automation system is performing the entire DDT. At level 3 (Conditional Driving Automation), the driver is not expected to monitor the environment permanently and the entire DDT is performed by the automated system. However, the driver is required to be in the loop to take back control in case of a potential emergency request of the vehicle. Next, at level 4 (High Driving Automation), the system takes over the entire DDT at certain roadway and environmental conditions without any expectations from the driver to monitor the environment. At level 5 (Full Driving Automation), the system full-time performs the entire DDT under all roadway and environmental conditions.

Apart from the levels of automation, connectivity is another innovation that will transform the road traffic system. Connectivity is the capability of a vehicle to communicate with other systems outside of the vehicle such as other vehicles, road users or the infrastructure. For example, cooperative adaptive cruise control (CACC) is a driver assistant feature that uses wireless communication to exchange information with a predecessor. CACC enables the vehicle to follow its leader, keeping shorter THWs compared to ACC which increases the capacity of the motorway significantly. In this thesis, ‘partial or fully automated vehicles (SAE levels 1–5) without connectivity’ are referred to as AVs, ‘partial or fully automated vehicles (SAE levels 1–5) with connectivity’ as CAVs, and ‘partial or fully automated vehicles (SAE levels 1–5) with or without connectivity’ as C/AVs.

Although CAVs have the potential to enhance traffic safety and efficiency, achieving their system wide effects will be challenging at low MPRs (Talebpour and Mahmassani, 2016; Pinjari, 2013). As an example, to increase the traffic capacity, CAVs need to form stable platoons which means following other CAVs at very short THWs. This will be extremely difficult due to low number of CAVs at low MPRs. Thus, these vehicles will be operating as single AVs, not being able to exploit their close car-following capabilities. Furthermore, C/AVs might be interrupted by MVs in mixed traffic. In other words, the interactions between MVs and C/AVs can reduce their potential efficiency and safety (Talebpour et al., 2017). The literature also suggests that MV drivers adapt their behaviour when interacting with platoons of CAVs by close car-following (Gouy et al., 2014; Yang et al., 2019). This behavioural adaptation can lead to unsafe situations given that human drivers have longer reaction times compared to CAVs and cannot manage smaller than normal THWs.

To overcome the above-mentioned challenges, researchers have suggested to reserve one lane of the motorways for automated driving. Concentrating CAVs on one lane and separating them from MV traffic can facilitate platooning of CAVs and consequently, increase the traffic efficiency (Xiao, Wang, & Arem, 2019; Amirgholy et al., 2020). However, knowledge on the design and operation of such a lane and their impact on human drivers’ behaviour in car-following and lane changing and its implications on traffic safety and efficiency is largely lacking.

1.2 Problem statement

Despite the increasing body of knowledge regarding the benefits of DLs in terms of traffic efficiency, the impacts of different design and utilization policies of DLs on the behaviour of human drivers remains a knowledge gap. A primary issue is to investigate the impacts of DLs on the behaviour of MV drivers and any potential behavioural adaptation. Furthermore, human drivers operating C/AVs would potentially interact with the system by switching between manual and automated driving modes or adjusting the system settings. Of particular interest is the impact of the presence and utilization policy of a DL on the behaviour of C/AV drivers in terms of preference to use automation and their driving behaviour.

The first step towards investigating the impacts of DLs on the behaviour of human drivers is to investigate their behaviour during driving in manual and automated mode, in mixed and in separated (via DLs) traffic, which represents the focus of this dissertation.

1.3 Research objectives, questions, and scope

The objectives of this thesis are threefold: (1) to develop a conceptual framework that identifies the knowledge gaps and provides a research agenda on the design and operation of DLs; (2) to investigate the impacts of the presence of a DL on potential behavioural adaptation of MV drivers in car-following and lane changing; (3) to study the impacts of the presence and utilization policy of a DL on CAV drivers' preferences to use automation as well as their car-following and lane changing behaviour. To achieve these research objectives, the following research questions will be addressed:

1. *What are the underlying factors that influence the design of dedicated lanes? To what extent are these factors addressed in the literature and what are the challenges for future research?*

A comprehensive overview is lacking in the literature regarding the relations between the deployment of C/AVs considering different MPRs, design and operation of DLs, driver behaviour, and traffic performance and safety. Such an overview is needed to identify the knowledge gaps and to provide a research agenda on the design and operation of DLs for C/AVs. The remaining questions addressed in this thesis are based on these insights and research gaps.

2. *What is the impact of the presence of a dedicated lane for CAVs on the behavioural adaptation of MV drivers in car-following and lane changing?*

One of the main concerns of mixed traffic with CAVs and MVs is the behavioural adaptation of MV drivers. This research question investigates the behavioural adaptation of drivers of manual vehicles in car-following and lane changing when driving adjacent to a DL and compares that to the behavioural adaptation when driving in a mixed traffic at a moderate MPR (i.e., without a DL).

3. *What are the impacts of the presence and utilization policy of a dedicated lane on CAV drivers' preference to use automation as well as their car-following and lane changing behaviour?*

This research question pertains to CAV drivers' interactions with the system. The literature reports that drivers may prefer to disengage automation and resume manual control in some situations such as approaching a slower leader or expecting vehicles cutting in. Also, adoption of smaller than normal THWs depends on the user's acceptance, trust, and preferences. This research question investigates to what extent a DL can impact the CAV drivers' preference to use automation as well as their car-following and lane changing behaviour.

This thesis focuses on identifying the possible influencing factors that should be considered in the design and operation of DLs on motorways and their impacts on the behaviour of drivers of MVs and CAVs. DLs on other types of roads, such as urban roads are not within the scope of this study. Furthermore, in this thesis we refer to a DL as an existing lane of the motorway dedicated to C/AVs. Therefore, designing a new lane as a DL is not included within the scope of this study. However, modifying the existing design of the lane (i.e., changing the demarcations) and defining traffic management strategies (i.e., utilization policies) are considered in this thesis. In addition, in empirical studies, we assume that DLs are dedicated to highly automated vehicles with connectivity (i.e., CAVs).

1.4 Research approach

The methodology for this research involves literature study, setup and performance of empirical experiments, and data analysis of driver behaviour. To accomplish this, first, a review of studies focusing on the influencing factors which need to be considered when designing and operating DLs was conducted. Following this, insights on the relationships between those influencing factors were revealed and the research gaps were identified. This first step resulted in a research agenda for the design and operation of DLs. Secondly, to gain empirical insights on MV and CAV drivers' behaviour in mixed versus separate traffic (via DLs) data was collected in the driving simulator. To be more specific, the following approaches were applied to achieve the research objectives and address the research questions:

A systematic review of the literature was first conducted (see Chapter 2) to develop the conceptual framework, which can be seen in Figure 1-2. The framework consists of the relations between driver behaviour, design and operation of DLs, and traffic performance and the environment. These are the three main components identified considering the MPR of C/AVs. Within each component, categories were created to organize the factors that should be investigated. Considering drivers, a distinction was made between drivers of MVs and C/AVs. A research agenda, including prioritization of the research needs, is proposed based on the conceptual framework. The framework also serves as a basis for the empirical studies reported in Chapters 3 and 4.

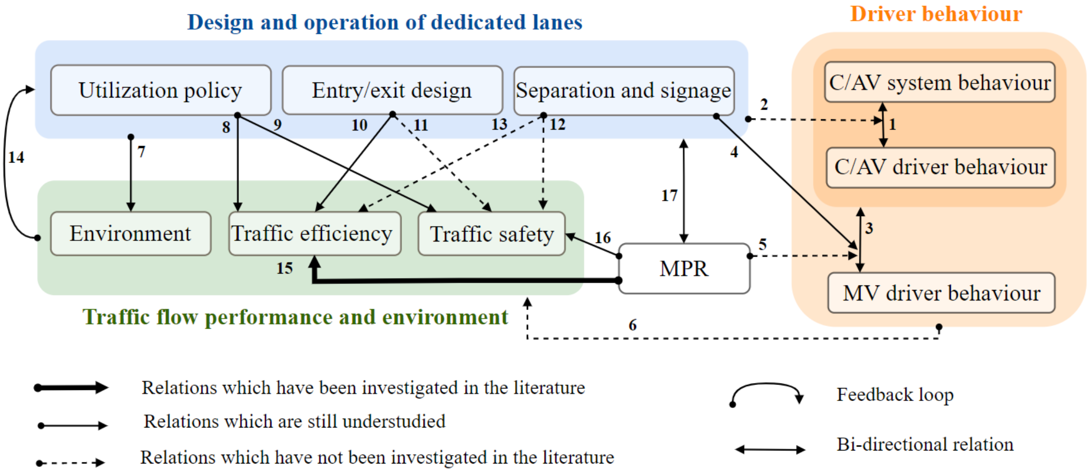


Figure 1-2 The conceptual framework for the relations between the design and operation of dedicated lanes, driver behaviour, traffic flow performance and the environment.

Performing a driving behaviour study with CAVs in real life is difficult as the number of CAVs on the road is still limited and the driving conditions cannot be controlled. Furthermore, having participants drive or interact with these vehicles in real life has ethical and safety implications. Therefore, a set of driving simulator experiments were used in combination with questionnaires to provide observational data on driver behaviour. Chapter 3 focuses on investigating the behaviour of MV drivers in mixed traffic on a road without a DL, and comparing that to the situation where MV drivers drive on a lane adjacent to a DL where CAV platoons drive. Chapter 4, on the other hand, focuses on investigating the behaviour of CAV drivers who have the possibility to choose between driving in an automated mode and resuming manual control in the presence of a DL. The driving simulator facilitates the design of the experiments in which participants could drive in different and novel situations without exposing them to any risk. In addition, it facilitates the deployment and manipulation of CAVs in the experiments in a way that would not have been possible in real-life due to practical, ethical, safety, and financial reasons. It was also possible to present the conditions and scenarios created in the same manner to all the participating individuals to draw accurate (unbiased) conclusions.

The surveys facilitated the investigation of the underlying human factors that influenced the driving behaviour of participants. The data gathered using surveys were the following: demographics, driving style, familiarity and experience with automation, trust in automation, presence (i.e. perceived immersion), and severity of simulation sickness symptoms during the drives in the driving simulator. All in all, the two driving simulator experiments in combination with the employed questionnaires facilitated capturing empirical data to investigate the impacts of DLs on the behaviour of drivers.

1.5 Contributions

In this section, the main scientific and practical contributions of this thesis are highlighted in section 1.5.1 and 1.5.2.

1.5.1 Scientific contributions

A conceptual framework for design and operation of DLs to pinpoint the research gaps and an agenda for research needs (Chapter 2). This conceptual framework represents one of the first attempts to develop a framework explaining the influencing factors which need to be considered when designing and operating DLs and provides insights on which relationships have been addressed in the literature and identifies those that have not yet been addressed or have been only partially addressed. Additionally, this chapter identifies the knowledge gaps and provides a research agenda on design and operation of DLs for C/AVs from three aspects: 1) challenges on design and operation of DLs; b) methodological challenges; c) research related challenges.

Insight into the impacts of the presence of a DL on the behaviour of MV drivers (Chapter 3). According to the conceptual framework, two main research gaps are the behavioural adaptation of MV drivers in mixed traffic and the impacts of a DL on this behavioural adaptation. This chapter contributes to the literature by filling these research gaps. Firstly, the impacts of DLs on the behavioural adaptation of MV drivers have been mainly investigated in the literature considering car-following behaviour. This chapter is one of the first studies to investigate the behavioural adaptation of MV drivers in lane change manoeuvres in addition to car-following; secondly, it investigates, for the first time to the best of the author's knowledge, if the behavioural adaptation happens in mixed traffic at moderate MPRs before implementing DLs; thirdly, reveals the impacts of a DL on this behavioural adaptation (if any) at a moderate MPR; and fourthly, investigates the relationship between behavioural adaptation and driving styles and characteristics of MV drivers.

Understanding of the impact of the presence and utilization policy of a DL on CAV drivers' preference to use automation and driving behaviour (Chapter 4). To the best of the author's knowledge, this is the first study that investigates the impact of a presence and utilization policy of a DL on CAV drivers' preference to drive in automated or manual mode and their driving behaviour in car-following and lane changing, considering relevant human factors.

1.5.2 Practical contributions

Besides the scientific contributions, the results of this thesis also contribute to society and practice in terms of policy, traffic modelling, infrastructure design, and developments of

C/AVs. These insights can help road authorities with the decision making for the medium to long term planning for accommodating C/AVs on road networks.

For *policy makers*, this thesis presents possible strategies for implementing DLs for CAVs. These strategies entail under which utilization policy the provision of DLs can offer benefit for all traffic. The utilization policies proposed in this thesis help policymakers and planners to recognize potential impacts of these strategies in practice and make informed decisions.

For *traffic modellers*, this thesis contributes to providing empirical foundation to increase the realism of microscopic traffic flow models. They can incorporate the empirical data from this thesis that describes the behaviour of drivers of MVs and CAVs, into their existing models when evaluating the performance of DLs. These insights are essential to more realistically evaluate the impacts of automated driving and dedicated lanes.

For *infrastructure designers*, this thesis designed road signs for DLs and investigated the impacts of demarcations and location of such lanes. The insights on driver behaviour in relation to the tested design achieved from the driving simulator experiments should be considered in the design and operation of future roads with DLs.

For *car manufacturers*, this thesis provides guidance by revealing the impact of lateral speed on drivers' preference to use automation in lane changing. This finding can help car manufacturers in designing C/AVs that are acceptable by a wider range of drivers.

1.6 Outline of the dissertation

The thesis outline is illustrated in Figure 1-3. The research questions posed in Section 1.3 are addressed in Chapters 2-4. The chapters in this thesis are structured as follows:

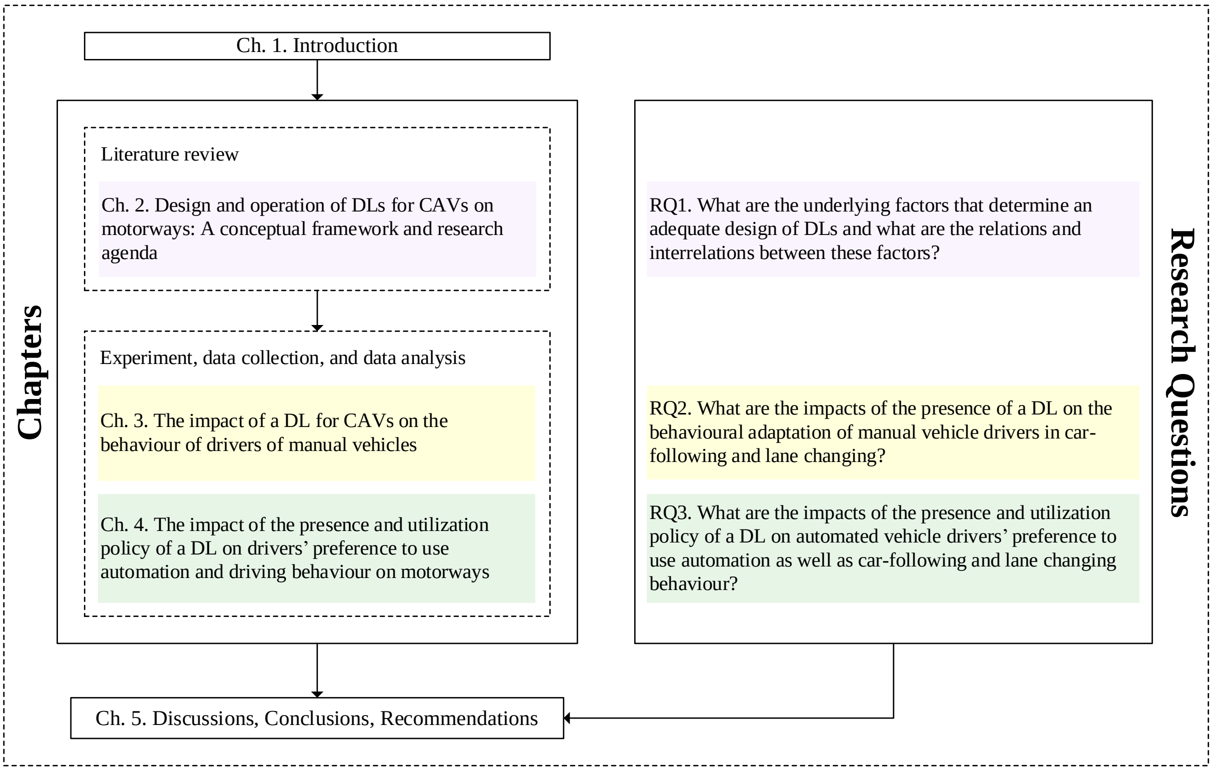


Figure 1-3 Overview of the thesis structure.

Chapter 2 proposes a conceptual framework based on a comprehensive review of the influencing factors which need to be considered when designing and operating DLs for C/AVs. It also identifies the research gaps and provides a research agenda on the design and operation of these lanes.

Chapter 3 presents an empirical study on the car-following and lane changing behaviour of MV drivers when driving in a mixed traffic with CAVs and compares that to the situation when they drive on a lane adjacent to a DL.

Chapter 4 investigates the impacts of the presence and utilization policy of a DL on CAV drivers’ preferences to use automation as well as their car-following and lane changing behaviour in different driving modes and on different lane types (i.e., normal vs. dedicated lanes).

Finally, Chapter 5 discusses the key findings and provides insights on design and operation of DLs. Those insights provide useful implications for Rijkswaterstaat, the Dutch operator for the main road network, policymakers and other road operators. Recommendations for practice and future research are also provided.

Chapter 2

Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda

In order to evaluate the performance of DLs, a conceptual framework is developed accounting for the factors that could affect the safety and efficiency of these lanes. This conceptual framework is underpinned based on the relevant literature on how the deployment of C/AVs, driver behaviour, and DL design and operation affect traffic safety and efficiency. Based on this conceptual framework, a research agenda identifying the knowledge gaps on DL design is proposed, which steers the direction of research in subsequent chapters of this thesis.

This chapter is based on the journal publication: **Razmi Rad, S.**, Farah, H., Taale, H., van Arem, B., Hoogendoorn, S.P., 2020. Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda. Transp. Res. Part C Emerg. Technol. 117, 102664. https://doi.org/10.1016/j.trc.2020.102664

2.1 Introduction

The increase of road traffic in the past few decades has led to several societal challenges such as congested road networks, deterioration of air quality and safety, and an increase in fuel consumption (European Road Transport Research Advisory Council, 2019). At the same time, the ongoing development of Information Communication Technology (ICT) has raised the interest of car manufacturers to apply such technology to assist drivers in their driving tasks and tackle these societal challenges. Systems, such as Adaptive Cruise Control (ACC) and Cooperative ACC (CACC) can enhance the traffic safety by the elimination of human errors (Fagnant and Kockelman, 2015) and increase the stability of the traffic flow by decreasing shockwaves (Van Arem et al., 2006). CACC systems also have the potential to improve the traffic flow efficiency due to shorter than normal time headways and communication between vehicles (Liu et al., 2018a) and have a positive impact on air quality by reducing fuel consumption (Ivanchev et al., 2017; Wan, Vahidi, & Luckow, 2016; Lu and Shladover, 2014). Such systems are among the main building blocks of connected and automated vehicles (CAVs) functionalities.

The Society of Automotive Engineers (SAE) identifies six levels of automation (SAE, 2018) ranging from level 0 (No Automation) to level 5 (Full Automation). The role of the driver decreases as the level of automation increases. At level 1, the driver needs to be in control of either the longitudinal or the lateral movement and at level 2 the vehicle controls both directions. While at both levels the human driver must continuously monitor the driving environment and is required to take back control in some situations. At levels 3 and 4, the system performs the entire driving tasks when engaged, without any expectations from the human driver to continuously monitor the system. However, the system may request the driver to intervene in some situations at level 3. At the highest level, level 5 (Full Automation), the vehicle can operate under full automated control on all types of roads and in all conditions. Despite the uncertainty regarding reaching level 5 (Nieuwenhuijsen et al., 2018), vehicles with levels 1 and 2 are already driving on our roads, and vehicles with levels 3 and 4 are operating as prototypes for testing their capabilities. Consumer vehicles with levels 3 and 4 are expected to be commercially available in the coming decade (Shladover, 2016). However, apart from the technology development, many requirements need to be met before the deployment of these vehicles takes place on our road network in terms of infrastructure, policy and regulations (Farah et al., 2018; Litman, 2018). Different studies have used different terms for automated vehicles. In this paper we refer to '*partial or fully automated vehicles (SAE levels 1-5) without connectivity'* as AV, *'partial or fully automated vehicles (SAE levels 1-5) with connectivity'* as CAV, and '*partial or fully automated vehicles (SAE levels 1-5) with or without connectivity'* as C/AVs.

Considering complex traffic situations, the implementation and deployment of C/AVs on motorways is challenging. One of the main concerns is the mixed traffic situation, where C/AVs and manual vehicles (MVs: SAE level 0) share the road. A key issue in this respect is that we lack knowledge regarding the interactions between C/AVs and MVs and their implications on traffic performance and traffic safety. There is some evidence in the literature that human drivers adapt their behaviour when they interact with platoons of CAVs. Such behavioural adaptation was found in driving simulator studies by Gouy et al. (2014) and Yang et al. (2019). When driving next to CAV platoons keeping short time headways, participants adapted the time headway and drove closer to their leader. Such reductions in time headways can lead to risky situations and even to accidents considering the longer reaction times of human drivers compared to CAVs (Wolterink et al., 2010; Schakel et al., 2010). However, the reason behind this change of behaviour and the extent to which it is considerable and dangerous is not yet well understood. Moreover, in a small-scale field test study, it was revealed that car following behaviour of MV drivers can be influenced by their level of trust in automation technology. MV drivers who have higher level of trust in automation, drive closer to their leader if it is known to be an AV, compared to when the lead vehicle is an MV (Zhao et al., 2020).

Regarding the traffic performance, platooning of CAVs will be less feasible at low Market Penetration Rates (MPR) of these vehicles. Even at higher MPRs, it would be possible that MVs interrupt CAV platoons (i.e. driver error, or cutting-in) leading to a decrease in platooning benefits and unsafe situations. Assigning a lane to C/AVs could not only improve the probability of platooning with increased concentration of these vehicles in one lane, but it could also decrease the interactions between C/AVs and MVs (Talebpour et al., 2017). However, dedicating a lane to C/AVs can increase the congestion in the remaining lanes for regular traffic and cause shockwaves near entry/exit areas of these lanes (Talebpour et al., 2017; Xiao, Wang, & Arem, 2019; Zhong, 2018).

Dedicated lanes for C/AVs have been proposed frequently as a potential scenario for the deployment of AVs on our road network (van Arem, de Vos and Vanderschuren, 1997; Lumiaho and Malin, 2016; McDonald and Rodier, 2015; Lee et al., 2018; Kockelman et al., 2016). A dedicated lane, (referred to as “DL” hereafter) is one of the existing lanes of a motorway on which only C/AVs (partially/fully automated vehicles with or without connectivity) are allowed. However, evidence based knowledge regarding the traffic safety and efficiency of different lane utilization policies resulting from the geometric design of DLs, the design of their entrances and exits, and the benefit of designing a transition lane, is very limited and restricted to conceptual design requirements mainly obtained from the Automated Highway Systems research (Tsao et al., 1993). Depending on the level of automation and defined regulations, lane changes towards DLs can be performed in an automated or a manual mode. Assuming that automated lane change is feasible, knowledge about drivers’ preferences regarding automated or manual lane change towards DLs is lacking. Moreover, DLs could provide support for C/AVs. Carreras et al., (2018) have defined five levels of infrastructure support for C/AVs, namely ISA levels. According to ISA, conventional infrastructure without any support for C/AVs is categorized as level E. Next, at level D, a digital map with static regulatory information is available. At level C, all relevant digital information in digital form is offered. At level B the infrastructure senses complete traffic situations at a microscopic level by specialized sensors. Finally at level A, C/AVs are able to optimize the overall traffic flow with the aid of infrastructure which is capable of traffic perception for the purpose of microscopic traffic management. It is recommended to study which level of infrastructure support is needed for a DL considering the type of vehicles that are allowed to use it.

To the best of our knowledge, there is no comprehensive overview of the relationships between the deployment of C/AVs, DL design and operation, driver behaviour, and traffic performance and safety. Despite the increasing body of knowledge about some of the relationships between these aspects, the literature lacks comprehensive studies investigating the combined effects of these aspects on the traffic efficiency and safety of DLs. We aim to present a comprehensive overview of the influencing factors which need to be considered when designing and operating DLs and provide insights on which relationships have been addressed in the literature and identify those that have not yet been addressed or have been only partially addressed. Therefore, the main aim of this study is firstly to present a conceptual framework that provides this overview; secondly, to identify the knowledge gaps and provide a research agenda on design and operation of DLs for C/AVs. It should be emphasized that we aim to confine this paper to examples which underpin the conceptual framework rather than giving a full literature review.

The remainder of this paper is structured as follows: In section 2.2 the scope of the study is presented followed by the conceptual framework which is presented in section 2.3. Section 2.4

underpins the conceptual framework with a literature review focusing on dedicated lane design configurations, as well as driver behaviour and their implications on traffic safety and efficiency. Section 2.5 identifies the knowledge gaps and proposes a research agenda based on the reviewed literature. Finally, section 2.6 describes the main conclusions of the paper.

2.2 Scope of the study

The aim of this paper is to identify and discuss the possible influencing factors that should be considered in the design and operation of DLs for automated and/or connected passenger vehicles on motorways. Dedicated lanes on other types of roads, such as urban roads, and the design of intersections is not in the scope of this study. Furthermore, in this paper we refer to dedicated lanes as an existing lane of the motorway dedicated only for fully or partially automated vehicles with or without connectivity. Thus we do not include within the scope of this paper the possibility of designing a new infrastructure or expanding the existing motorway infrastructure by building a dedicated lane. However, modifying the existing design of the lane (such as changing the demarcations and access type) and defining traffic management strategies (i.e. utilization policies) are within the scope of this paper. In the conceptual framework we illustrate how the different considered aspects are connected and influence each other.

Although several other factors like road surface rutting performance (Chen, Balieu, & Kringos, 2016), fairness, pricing (Litman, 2019) and impacts of implementing DLs across the transportation network (Chen et al., 2017) are of concern when these lanes are implemented, they are not within the scope of this study.

2.3 Conceptual framework

Starting from the notion that road design influences driver behaviour (Ariën et al., 2017; Baas & Charlton, 2005; Martens, Comte, & Kaptein, 1997) and impacts traffic safety and efficiency (Wang et al., 2013), a conceptual framework is derived, as illustrated in Figure 2-1. The conceptual framework particularly focuses on relationships that influence traffic safety and efficiency where one or more lanes of a motorway are dedicated to C/AVs.

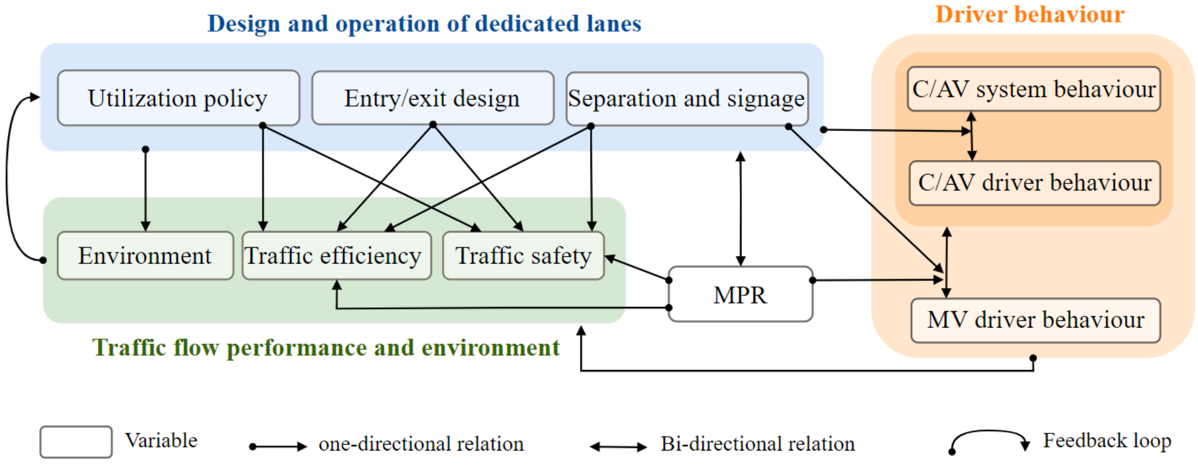


Figure 2-1 Conceptual framework for the relations between the design and operation of dedicated lanes, driver behaviour, traffic flow performance and the environment.

As mentioned earlier, with the deployment of C/AVs the behaviour of MV drivers could be affected. Such effects include shorter time headways and gaps that MV drivers may adopt in car following and lane changing manoeuvres, respectively. Eventually this can influence the traffic efficiency and safety. DLs with physical separation from the normal lanes may reduce the negative effects of behavioural adaptations of MV drivers (Yang, Farah, Schoenmakers & Alkim, 2019) and as a result increase safety. By concentrating C/AVs on one lane, a DL could also increase the chance of platoon formation and as a result improve traffic efficiency. In general, it is clear that, the MPR plays an important role in all the relations illustrated in the conceptual framework. In the next section, these relations are described in more detail and are underpinned using studies available in the literature.

2.4 Underpinning the conceptual framework based on the literature

This section underpins the conceptual framework based on previous studies and evidence from the literature. We particularly focused on the literature addressing the relations (arrows) in the conceptual framework.

For this purpose, first an initial search in Scopus, Web of Science, Google Scholar, and Transport Research International Documentation (TRID) databases was performed to identify the relevant papers, using the following keywords and the additional keywords illustrated in Table 2-1 for each associated area of implication: ‘automated vehicles’, ‘autonomous vehicles’, ‘driverless vehicles’, ‘(cooperative) adaptive cruise control’, and ‘platooning’. Then, a backward and forward snowballing technique was used to select further literature in case the papers from the initial search did not result in studies covering the arrows in the conceptual framework. Finally, a complementary search was performed to check the identified research gaps after reviewing the literature. In total, 83 scientific articles were reviewed and included in this paper.

In the following sub-sections we attempt to underpin the relations presented in the conceptual framework using the existing literature with the ultimate aim to identify the knowledge gaps on dedicated lane design and operation for C/AVs and to provide a research agenda.

Table 2-1 Keywords used for each associated area of implication

Area of Implication	Keywords
Driver behaviour	Behavioural adaptation, carry-over effect, car-following behaviour, lane-changing behaviour, transition of control, authority transition,
Road design	Dedicated lanes, managed lanes, HOV lanes, HOT lanes, express lanes, reserved lanes, lane allocation, buffer separated lanes, dedicated OR managed lane AND limited access, dedicated OR managed lane AND continuous access, dedicated OR managed OR reserved lane AND demarcations, dedicated OR managed lane AND entry OR exit configurations, dedicated OR managed lane AND utilization policy, dedicated OR managed lane AND distribution policy
Traffic flow efficiency	Dedicated OR managed OR reserved lane AND traffic efficiency OR throughput OR capacity, travel time
Traffic safety	Dedicated OR managed OR reserved lane AND traffic safety OR shock waves

2.4.1 Dedicated lane design and operation

Research regarding the design aspects of DLs was first initiated in the 1990s by Automated Highway System (AHS) research which proposed major design concepts for full automation of highways (Hitchcock, 1995; Tsao et al., 1993; Varaiya, 1995; National Automated Highway System Consortium, 1997). The details of the design concepts are described in Table 2-2.

Table 2-2 Limited entry/exit configurations suggested by literature

Authors	Specifications	Impacts found
Tsao et al. (1993)	– Segregated Highway (without mixing automated traffic with manual traffic) with CAVs – Segregated Highway with AVs – Shared Highway (with dedicated lanes) with Barriers and CAVs – Shared Highway with Barriers and AVs – Shared Highway without Barriers and with CAVs – Shared Highway without Barriers and with AVs	No impact assessment was conducted
Varaiya (1995)	– The left most lane is dedicated to C/AVs with access points of at least 2 km apart via a transition lane, two right lanes are manual lanes. – Two left most lanes are DLs with no designated entry/exit. Dedicated elevated ramps provide access to the second most left lane. At least 5km not elevated section of road exists between on and off-ramps. The two right lanes are manual lanes – Two left most lanes are DLs. Dedicated elevated ramps provide access to both DLs. At least 5km not elevated section of road exists between on and off-ramps. The two right lanes are manual lanes – The leftmost lane is DL consisting of an at least 2km elevated structure providing access to on- and off-ramps. The other 3 lanes are normal lanes. This arrangement is also suggested with two manual lanes and two DLs as well.	No impact assessment was conducted
Ioannou (1997)	– At-grade (lane conversion): one lane is converted to DL – At-grade (median): Available space within the median is used for C/AV lanes – At-grade (median and shoulder): A combination of available space within the median and beyond the outside shoulders is used to expand the freeway laterally to add a sufficient number of lanes for C/AVs – At-grade (shoulders): Available space beyond the outside shoulders is used to expand the freeway laterally to add a sufficient number of lanes for C/AVs – Above-grade (median): Available space within the median is used for the structure supporting the elevated C/AV lane – Above-grade (shoulders): available space beyond the outside shoulders is used for the structure supporting the elevated C/AV lane – Below-grade (tunnel): A C/AV lane constructed below the existing grade level of the freeway	These configurations were ordered from the easiest to the most difficult to deploy according to the criteria below: 1. Right-of-way, 2. Environmental impacts, 3. Cost, 4. Natural hazards, 5. Construction impacts

According to these design concepts, the C/AV lane is always the fastest lane of the motorway which might be a lane added to existing lanes or an already existing lane which is reserved for C/AVs. Entry to these lanes should be performed via a transition lane adjacent to the C/AV lane where C/AVs can transition between manual and automation as well. C/AVs need to undergo check-in and check-out before entering the C/AV lane at specific locations on the transition lane. This transition lane should be long enough to guarantee the required distance for executing entry and exit manoeuvres. On- and off-ramps might be the conventional, already existing at-grade ones which are shared between C/AVs and MVs, or might be separated above-grade/below-grade structures dedicated to C/AVs only. However, the use of above-grade/below-grade structures has been discouraged due to the high cost of construction and seismic safety hazards (Ioannou, 1997). According to these design configurations, a minimum of four lanes would be required taking into account one C/AV lane, one transition lane, and a minimum of two manual lanes. This configuration might not be feasible for existing 3-lane motorways without further widening. Note that, according to this design, MVs are not allowed to use the DLs and the transition lanes which can greatly increase their travel time. Obviously, extensive research is needed to investigate the implications of such design on traffic safety, efficiency, liability, constructability, and human factors (National Automated Highway System Consortium, 1997).

The Automated Highway System concept has been evaluated regarding safety and efficiency using simulations, mostly considering the segregation scenarios meaning the full automation of highway without presence of MVs (Hearne and Siddiqui, 1997; Kanaris et al., 1997; Carbaugh et al., 1998; Godbole and Lygeros, 2000).

More recent studies have investigated the impacts of dedicating an already existing lane (DL) on traffic performance and traffic safety as summarized in Table 2-3. As it is reported in Table 2-3, simulation studies have shown that dedicating a lane to C/AVs have the potential to improve the traffic performance. However, the effectiveness of DLs highly depends on the penetration rate of C/AVs in traffic. For example, microscopic simulations have shown that implementing DLs at MPRs lower than the lane saturation level degrades the traffic performance and increases the travel time of MVs due to the fact that MVs are restricted from using that dedicated traffic lane. However, when the MPR increases beyond a certain level, implementing DLs not only improves the traffic efficiency (Van Arem, Van Driel, & Visser, 2006; Fakharian Qom et al., 2016; Ivanchev et al., 2017; Xiao, Wang, & Arem, 2019; Amirgholy et al., 2018; Vander Laan & Sadabadi, 2017; Ye & Yamamoto, 2018; Melson et al. 2018; Amirgholy et al., 2020), but also improves the traffic safety evaluated by surrogate safety indicators and their standard deviations (Rahman and Abdel-Aty, 2018) as well as shockwaves reduction (Van Arem et al., 2006). A recent study by Liu et al. (2020) shows that implementing DLs can also improve fuel efficiency and that this is more evident at low MPRs.

Other studies have reached different results in that the implementation of DLs would increase the throughput but can cause shockwave formations due to mandatory lane changes towards DLs (i.e. bottlenecks) (Talebpour et al., 2017; Princeton and Cohen, 2011). If on- and off-ramps are dedicated to C/AVs, the lane changes across the mixed traffic will not be necessary (Varaiya, 1995). However, this might not always be possible due to reasons such as lack of space and high costs of elevated ramps. Another strategy which was tested by Liu et al. (2018c), is the early lane change advisory message. With this strategy, lane changes are performed at a further distance to on- and off-ramps which can greatly reduce the last minute lane changes.

A level of penetration rate could be considered as a “turning point” for changing the traffic performance, where below it, implementing DLs can degrade the traffic performance and above it could enhance it. Depending on the number of lanes, the configurations of DLs, and traffic flow conditions, the “turning point” has been reported at different rates in the literature: ranging from 15% (Yang et al., 2019) to 50% (Ivanchev et al., 2017; Vander Laan & Sadabadi, 2017; Xiao et al., 2019; Arnaout and Bowling, 2014). Another reason behind these differences is because simulation studies were conducted under different assumptions and C/AVs were programmed to behave differently as further detailed in Table 2-3. For instance, a review of Time-Headway (THW) distributions in a mixed and pure CAV scenario by Ghiasi et al. (2017) showed that the THW between two MVs ranges from 0.7 to 2.4s, those for a CAV following an MV from 0.5 to 2.6s, those for an MV following a CAV from 0.6 to 2.6s, and those between two CAVs from 0.3 to 2.0 seconds. These differences can significantly affect the traffic performance analysis (Ghiasi et al., 2017). Moreover, different access types of DLs and utilization policies could have an impact on traffic performance and traffic safety. This is reviewed in the following sub-sections.

Table 2-3 Summary of literature regarding the impact of DLs on traffic performance

Authors	Tools/AV specifications	Type of road	Impacts found
Van Arem et al. (2006)	– MIXIC traffic simulation – Intra-string THW: 0.5s – Inter-string THW: 1.4s – CACC, No lateral automation – Penetration rates in steps of 20% (0% - 100%)	Four-lane motorway with a lane drop, with DL in some scenarios	– At MPRs < 40%, the DL leads to a degradation of performance (lower speeds, higher speed variances, and more shockwaves). – At MPRs >60% the DL could improve traffic stability by lower speed variances, but only for the high-volume stretch before the bottleneck
Ivanchev et al. (2017)	– Agent-based macroscopic simulation – THW: 0.5s ,1 s – No connectivity for AVs	The whole road network of the city of Singapore in morning commute hours	– Travel time of MVs increases significantly at MPRs ranging 40-50%. – Roads leading to the highways exhibit higher demand and congestion since more AVs use the highways to reach the DLs
Vander Laan et al. (2017)	– Adopted Newell (2002) linear car-following to model AVs, applied in CORridor MACro simulation software – Three scenarios were compared using THWs 0.7s, 0.5s, and 0.3s – No connectivity for AVs – Merging and friction effects were ignored	Four-lane highway with one DL was simulated from 4:00–6:00 PM on weekdays	– Best performance is seen at MPRs 30%, 40%, and 50% for THWs 0.7s, 0.5s, and 0.3s respectively. Afterwards, the traffic degrades significantly.
Liu et al. (2018b)	– CACC modelling framework was developed based on the NGSIM oversaturated flow human driver model (Yeo et al., 2008) – CACC car following model derived from the field CACC tests (Milanés and Shladover, 2014) – Vehicle dispatching model assigned the CACC vehicles to DLs, or the adjacent lane if DL was at capacity – Introduced anticipatory lane changing – MVs were equipped with Vehicle Awareness Devices (VAD) – THW of CACC vehicles: 0.6 s (57%), 0.7 s (24%), 0.9 s 7%, and 1.1 s (12%).	Two networks were tested: a) four-lane freeway segment of 7km long with an on- and an off-ram; b) four-lane freeway segment of 18-km long with complex on and off-ramps and weaving bottlenecks	– DL and VAD strategies significantly improved the pipeline capacity (8-23%). – The DL strategy performs slightly better than the VAD strategy. – In the presence of DL, the VAD strategy does not improve the capacity compared to individual use of each strategy since there are many VAD vehicles which are not needed as platoon leaders. – Both strategies increased the bottleneck capacity while VAD performed better than DL.
Rahman et al. (2018)	– VISSIM microscopic simulation – THW for CAVs: 0.6s – Car following models used: o MVs: Wiedemann 99 o CAVs: IDM along with three platoon joining schemes: rear, front, and cut-in joins	A congested expressway with 17 weaving segments with one DL MPR: 40%	– Five surrogate safety measures tested: standard deviation of speed, time exposed time-to-collision, time integrated time-to-collision, time exposed rear-end crash risk index, and sideswipe crash risk – The longitudinal crash risk was higher in the baseline scenario without CAVs compared to scenarios where platooning was allowed on all lanes and the scenario with DLs. – DLs outperformed the other two scenarios with improved longitudinal safety.
Xiao et al. (2019)	– Microscopic traffic simulator, MOTUS – CACC vehicles – Intra-string THW: 0.6s-1.1s – Inter-string THW: 1.5s – Lane change was modelled according to LMRS (Schakel et al., 2013)	3-5 lane Highway with one HOV lane converted to DL with continuous access, operating in the morning peak (06:00 - 10:00 AM)	At MPRs (%): o **10-20**: congestion and travel time of the whole vehicle fleet increased o **30**: congestion and travel time was comparable to the reference case (the leftmost lane is HOV lane) o **40-50**: congestion and travel time reduced – Speed reduction was observed at bottlenecks due to the friction effect

2.4.1.1 Dedicated lane entry/exit configurations

As reviewed in the previous section, limited entry/exit areas for DLs via transition lanes have been frequently recommended by the early research on Automated Highway Systems (Hitchcock, 1995; Tsao et al., 1993; Varaiya, 1995; National Automated Highway System Consortium, 1997). Assuming that DLs are accessible to C/AVs only from designated entries/exits, it is crucial to investigate the efficiency and safety implications of different lengths of entries/exits and the distance between two successive access points considering different MPRs.

Table 2-4 Summary of literature comparing different access types of DLs

Authors	DL Configurations	Method/AV specifications	Impacts found
Zhong (2018)	- Dedicated lane to CAVs with continuous access (DL); - DL with limited access (DLA).	- Multi-objective optimization control algorithm; - Objectives for a CACC platoon: ○ mobility ○ comfortability ○ emission ○ fuel consumption	- DLA performed always better than DL in terms of network travel time and throughput at MPR ranging 10-40%. However, DL outperformed DLA at network throughput when MPR reached 45%; - DLA outperformed the baseline in terms of the network throughput and travel time only at MPR of higher than 22% and 28% respectively. While for DL this improvement happened at higher MPRs (26% and 30% respectively); - The highest percentage for platooned CACC is 51% at 50% MPR on DLA. While DL decreased platooning probability at all tested MPRs.
Yang et al. (2019)	- DL with a) continuous and b) limited access - Weaving section length: a) 600m, b) 800m, and 1000m	VISSIM microscopic simulation THW: 0.5s Platoon size: 2-5 CAVs	- Access type: Traffic flow increased that of baseline from MPR=15-20% for continuous access and MPR=30-35% for limited access - Weaving section length: caused no significant change in traffic flow.

Despite the large body of research on Automated Highway Systems in the 1990s which recommended limited entry/exit configurations for DLs (Ioannou, 1997; Tsao et al., 1993; Varaiya, 1995; Hitchcock, 1995), more recent research has investigated the impacts of the continuous access type of DLs without any transition lane on traffic performance. Continuous access offers the possibility of changing the lane and joining the platoons on a DL continuously. This can degrade the traffic performance by too many lane changes between the DL and the adjacent lane which is called friction effect (Guin et al., 2008). In addition, in such configuration, joining CAVs might force the platoons to dissolve (Zhong, 2018). However, this depends on the cut-in vehicle characteristics (Milanés and Shladover, 2016). If the cut-in vehicle is not equipped with connectivity (i.e. ACC), the very next vehicle in the platoon needs to switch from CACC to ACC which can cause an increase in the time headway error affecting the speed of the vehicle. On the other hand, if the cut-in vehicle is equipped with connectivity (i.e. CACC), this error is significantly smaller since the follower vehicle handles the cut-in vehicle without causing major perturbations. Also, some platooning strategies could help mitigate the negative effects of cut-in issues. If CAVs are allowed to merge into the gaps between two platoons and not within a platoon when changing lane towards DLs, platoons are not forced to split (Liu et al., 2018b). Literature suggests that with different types of access configurations of DLs, the “turning point” of traffic performance may change (Yang et al,.

2019; Zhong, 2018) (see Table 2-4). For example, in the study of Yang et al, (2019), a DL with continuous access improved the traffic performance at lower MPRs compared to limited access. However, Zhong (2018) suggested that a limited access configuration improves the traffic performance at lower MPR compared to continuous access. This could have happened due to the differences in lengths of the different study sections and the number of lanes in the simulation. On the other hand, dedicating separated entries/exits are expected to outperform the other two designs (at-grade limited and continuous access) in terms of traffic performance and safety due to minimizing weaving on manual lanes (Hall et al., 2001; Varaiya, 1995).

Table 2-5 Summary of literature regarding access types of HOV lanes

Authors	Lane configurations	Impacts Found
Hearne (1998)	- Investigated accident statistics on barrier separated HOV lanes in the years of 1994 and 1995	- Since 91% of the accidents were attributed to rear end, sideswipe, or hitting concrete barriers mostly due to human error, they suggested that elimination of 93-97% of accidents would be possible theoretically with the elimination of human error on an automated highway system.
(Jang et al., 2009)	- Collision data from the Traffic Accident Surveillance and Analysis System for two types of HOV facilities were examined: - continuous access - limited access, considering: a) shoulder width, b) length of the access, and c) proximity of the access to nearest ramps	- Higher shoulder widths decrease accidents. - The limited access exhibited a higher collision rate. - Entry/exits with short access length (~402 meters) which were located near to on- or off-ramps (within ~483 meters) had significantly higher accident rates.
Jang & Chan (2013)	- Four types of HOV operations were evaluated: ○ part-time continuous access ○ full-time limited access with buffer separation ○ full-time continuous access ○ part-time limited access with buffer separation.	- Continuous access HOV lanes lead to higher speed differences when normal lanes are congested - Vehicle-mile-travelled on both configurations are comparable. However, limited access has wider variations - Limited access separates the traffic safely with preventing too many lane changes as well as last-second traffic weaving manoeuvres for lane changing

Few studies have examined the performance and safety implications of different entry/exit configurations of other types of managed lanes such as HOV lanes (Table 2-5). Hearne (1998) investigated accident statistics on barrier separated HOV lanes with limited access in the years of 1994 and 1995. Since 91% of the accidents were attributed to rear end, sideswipe, or hitting concrete barriers mostly due to human error, they suggested that elimination of 93-97% of accidents would be possible theoretically with the elimination of human error on the automated highway system. Also, limited access has shown to be safer in preventing too many lane changes and last-second traffic weaving manoeuvres to enter the managed lane (Jang et al., 2009). On the other hand, collision data shows higher accident rates in the vicinity of the entry/exit area of these types of lanes, especially when an entry/exit with a short length is located near an on- or off-ramp (Jang et al., 2013). This can be explained by the fact that lots of lane-changes take place downstream of on-ramps and upstream of off-ramps since drivers want to access their desired lane. This phenomenon is called turbulence. According to Van Beinum et al. (2016), “Turbulence is defined by headway changes and a changed distribution of traffic over the different freeway lanes. Corresponding aspects of driving behaviour are for example deceleration, evasive actions or (anticipating) lane changes”. Thus, it can be recommended that the limited entry/exit areas of DLs be located outside the turbulence area to avoid frequent lane changes which may increase the level of turbulence and accordingly the risk of accidents. As calculated by Van Beinum et al. (2018), turbulence continues 900 meters after the on-ramp and starts 1000 meters before the off-ramp on a 3-lane motorway. These results suggest that the entry/exit areas of managed lanes should be located outside the turbulent area that occurs after on-ramps and before off-ramps. This distance could vary, depending on the traffic and number of lanes which would require different number of lane changes towards the on- or off-ramp to and from the managed lane. Considering DLs, it is of relevance to investigate how turbulence lengths will change with increasing penetration rates of C/AVs.

The turbulence length may decrease at higher MPRs since CAVs are more precise and can communicate with each other. However, depending on the maximum CAV platoon size policy, the turbulence length may even increase if a platoon with a high number of CAVs is allowed to change lane towards DL without splitting. Changes in the turbulence could also change the recommended proximity of the entry/exit to the nearest on- or off-ramps. In addition, the length of entry/exit of HOV lanes is currently defined based on the number of vehicles using this lane. It could be hypothesized that with different MPRs we need to consider a certain length for these access points.

2.4.1.2 Dedicated lane utilization policy

Dedicated lanes may be designed with different lane use policies. These policies define how to use the DL (i.e. mandatory vs. optional use; and speed limits).

Limited research exists which investigated the impact of different DL utilization policies on human driver behaviour and traffic efficiency. For instance, a higher speed limit for DLs has been proposed by previous research studies (Ye and Yamamoto, 2018), which raises questions, such as: can a higher speed limit policy for traffic on DLs influence manual vehicles’ driving speeds?

Few studies have investigated the implications of different DL policies on traffic performance using various microscopic simulation models or by deriving analytical models (see Table 2-6). The results of these studies confirm that there is no best policy with respect to traffic safety and efficiency which is suitable for all MPRs. For instance, at low MPRs, a mixed traffic on the fast lane or dedicating the fast lane to both C/AVs and HOVs is suggested by some studies (Chen et al., 2017; Zhong, 2018; Ong & Kamalanathsharma, 2019). This is because it is not efficient to dedicate a lane to a low percentage of the whole vehicle fleet. At higher MPRs (starting from 25%), dedicating the fast lane to C/AVs could increase traffic throughput and enhance travel time at the network level. This confirms the findings of the study by Chen et al. (2016) who developed an optimization model to propose a time-dependent deployment plan for dedicated lanes to minimize the social costs and promote the adoption of AVs. According to their findings, DLs should be deployed progressively following the evolution of MPR. In line with many other studies, they suggest not to deploy DLs widely until the MPR is relatively high (at least 20%). However, this will be achieved with optional utilization of DLs meaning that C/AVs are allowed to operate on normal lanes as well (Talebpour et al., 2017). This is because forcing C/AVs to only use the DLs, can cause shockwave formations due to mandatory lane changes towards these lanes. Thus, utilization policies might need to be changed with the increase in MPR. In addition, impacts on platooning possibility and the behavioural adaptation of MV drivers in mixed traffic should be taken into account.

Table 2-6 Summary of literature regarding utilization policies of dedicated lanes

Authors	DL Utilization policy	Method/AV specifications	Impacts found
Chen et al. (2017)	- **(A, R)** left lane only allows CAV platoons, right lane only allows MVs; - (M, R) left lane allows mixed traffic, right lane allows MVs only; - (A, M) left lane only allows CAV platoons, right lane allows mixed traffic	Analytical study MPRs: 0-100%	(**A, R**): leads to lower capacity until the penetration rate at which both lanes reach their respective physical lane capacities[1] (Pcric) (**M, R**): Suitable policy for MPR< Pcric (**A, M):** Suitable policy for MPR> P_{cric}
Talebpour et al. (2017)	- AVs must go to the DL and they can operate automated everywhere (forced everywhere); - AVs must go to the DLs but must operate manually in normal lanes (forced reserved); - AVs can use the DL and they can operate automated everywhere (optional everywhere).	Microscopic simulation study MPRs: 0%, to 30% in steps of 10%	- **Forced** everywhere: increased the congestion and scatter in the fundamental diagram and caused shockwave formation due to the mandatory lane changes towards DLs - Forced reserved: Increased congestion and shockwaves but decreased average travel time - Optional everywhere: reduced congestion and the scatter in the fundamental diagram. At 70% MPR, improved throughput of the normal lanes by 200 vphpl compared to the situation without DL. The best scenario in terms of travel time reliability.
Zhong (2018)	- All vehicles can drive on all lanes (UML) - One lane is allocated to HOVs and CAVs (MML) - One dedicated lane to CAVs with continuous access (DL) - DL with limited access (**DLA**).	Multi-objective Optimization control algorithm MPRs: 0% (baseline) to 50% in steps of 10%	- **UML**: network travel time, throughput, and travel time reliability improved at all tested MPRs compared to all other strategies. - MML: Second best strategy after UML in terms of network throughput, travel time reliability, and speed variance at all tested MPRs. Led to the highest platooning probability for MPRs<25%. - DLA: only started to outperform the baseline after MPRs around 25%, 38%, and 30% in terms of network throughput, travel time, and speed variance respectively. Travel time reliability increased before MPR=40%. Travel time for CACC vehicles decreased drastically. The best strategy for platooning probability at MPR=25%. - **DL**: Always fell behind other strategies except for travel time of CACC vehicles. Only outperformed DLA at network throughput when MPR=45%. Reduced platooning probability at all tested MPRs.

1: Is defined as the maximum sustainable flow for given proportions of AVs and MVs in traffic streams (independent of the AV penetration rate)

Table 2-6 (continued)

Authors	DL Utilization policy	Method/AV specifications	Impacts found
Ong et al. (2019)	- four scenarios were tested: a) 10% CACC + HOV with 1 DL, b)25% CACC with 1 DL, c)35% CACC with 1 DL, and d) 45% CACC with 1 DL - DL was separated via double solid lane marking and limited access was allowed on designated dashed lane striping	Microscopic simulation study MPRs: 10%, 25%, 35%, and 45%	At low MPRs, sharing CACC vehicles with HOVs prevented congestion on normal lanes. The highest increase of throughput compared to the baseline happened at 35% CACC with 1 DL
Mohajerpoor and Ramezani (2019)	Four lane use policies were defined n a two-lane per direction motorway: - Policy A: one lane is dedicated to CAVs and one lane to MVs - Policy B: CAVs and MVs could use both lanes - Policy C: one lane is dedicated to CAVs and the other lane could be used by both - Policy D: one lane is dedicated to MVs and the other lane could be used by both	Analytical study MPRs: 0-100%	- Depending on the expected percentage of CAVs in the traffic stream (EPR), under the general (stochastic) arrangement of vehicles in the mixed lanes, the best lane utilization policy in terms of expected delay is: ○ Policy D for 0% ≤ EPR ≤ 50% ○ Policy A for < 50% EPR < 65% ○ Policy C for 65% ≤ EPR ≤ 100% ○ Above all, policy B returns near optimal delays for all the EPR ranges

Liu and Song (2019) proposed a new concept of autonomous vehicle/toll (AVT) lanes, as an alternative to DLs, when the MPR is low. AVTs grant free access to AVs and allow MVs to access these lanes by paying a toll. According to the results, implementing AVTs could significantly improve the system performance under the assumption that AVs keep smaller headways compared to MVs. In a conservative AV scenario when AVs keep larger headways than MVs, according to the authors, AVs should be tolled instead of MVs.

2.4.1.3 Type of separation between automated and manual vehicles

Basic infrastructure requirements, such as clear and harmonized road signs and lane markings should be met before deployment of C/AVs on public roads (Lu et al., 2019; Nitsche et al., 2014). The National Automated Highway System Consortium (1997) has introduced 3 types of separation: a) Virtual barrier: a paint stripe between normal lanes and DLs; b) Buffer zone: a spatial separation between normal lanes and DLs ranging from 2-14 feet (~0.6-4.3m); c) Physical barrier: a barrier such as a concrete barrier. Dimensions of such a barrier should be investigated further. Each of these types has positive or negative impacts on driver behaviour, traffic flow efficiency and safety which is still understudied. As it can be seen in Table 2-7, different types of separation for managed lanes (i.e. dedicated, HOV, or express lanes) have impacts on driver behaviour (Yang et al., 2019; Awan et al., 2018).

Table 2-7 Summary of literature regarding the separation of managed lanes

Authors	Separation	Tools/scenario description	Impacts found
Awan et al. (2018)	- Hard separation with tubular delineators and vegetation or grass strip - Soft separation with solid double line and cross hatch marking	**Driving simulator:** Participants drove on an express lane which was closed upstream due to an accident. All vehicles were manual.	Hard separation is more effective in restricting drivers to cross the separation
Yang et al. (2019)	- Hard separation with guardrails - Soft separation with buffer	**Driving simulator:** CAV platoons drove on DLs with different types of separation and MV drivers drove on the adjacent lane	MV drivers were less influenced by behaviour of CAVs when DLs were separated with guardrails

In general, hard separation has shown to be more effective in restricting drivers not to cross the separation (Awan et al., 2018). Furthermore, drivers are less influenced by the behaviour of CAV platoons in adjacent lanes due to fewer interactions (Yang et al., 2019). In the case of DLs, a hard separation between DLs and transition lanes and also between transition and manual lanes is necessary for safety and efficiency reasons (Tsao et al., 1993; Hitchcock, 1995). Although hard separations separate the automated and manual traffic more clearly, continuous access or part-time operation of DLs (i.e. peak hours) will not be possible with this separation type. Besides, in case of emergency, C/AVs need to exit the DLs immediately which is not possible with hard separations such as guardrails. Also, hard separation is not attractive for drivers making them feel "fenced in" (Varaiya, 1995). Moreover, Tsao et al. (1995) found more crashes near the beginning of highway sections with barrier compared to the section without barrier. This result was found conducting a simulation study of a 10 km section of a highway with one DL, one transition, and one normal lane. Access areas of 100 m were provided every 1 km between the DL and the transition lane. On the other hand, soft separations or pavement demarcations allow part-time operation of DLs and continuous access/egress which allows for platooning along the whole stretch of the road. Examples of separations can be seen in Figure 2-2.

Soft separations, Awan et al. (2018)

Soft separations, Yang et al. (2019)

Hard separations, Awan et al. (2018)

Hard separations, Yang et al. (2019)

Figure 2-2 Examples of hard and soft separation on managed lanes used in the literature.

In summary, studies have rarely focused on the design of DLs in terms of demarcations and access types. Studies regarding the impacts of utilization policies of DLs have mostly considered longitudinal automation without considering automation and connection in transient manoeuvres. In the literature, there are studies which have proposed lane change algorithms for C/AVs (Nie et al., 2016; Chandra et al., 2018; Bae et al., 2019). It is recommended to consider these algorithms for modelling lane changes towards DLs which could have impacts on traffic stability and the operation of the entry/exit points of DLs.

The design and operation of the dedicated lanes will largely affect drivers' behaviour. The following section reviews the driver behaviour from the viewpoint of an MV driver and a C/AV driver.

2.4.2 Driver behaviour

This section reviews the driver behaviour from the viewpoint of an MV driver and a C/AV driver. Regarding MV drivers, the change in their behaviour as a consequence of driving next to CAV platoons, namely behavioural adaptation, is reviewed. This provides knowledge regarding the interaction between CAVs and MVs and gives insights on the implications of separating CAVs and MVs via DLs. Considering C/AV drivers, the literature regarding behavioural adaptation as a result of experiencing driving with C/AV, drivers' tendency to switch from automated to manual mode and vice-versa (i.e., transition of control), and their preferences in car following and lane changing while driving a C/AV, which has impacts on traffic efficiency and safety, is reviewed.

2.4.2.1 Behavioural adaptation

Behavioural adaptation is defined as: "any change of driver, traveller, and travel behaviours that occurs following user interaction with a change to the road-vehicle-user system, in addition to those behaviours specifically and immediately targeted by the initiators of the change" (Rudin-Brown and Jamson, 2013).

Behavioural adaptation may be direct or indirect, meaning that it is intended or unintended by the designer, respectively. It might occur in drivers of C/AVs as well as drivers of MVs. MV drivers may adapt their behaviour while being exposed to CAVs (Gouy et al., 2013; Gouy et al., 2014; Yang et al., 2019), whereas C/AV drivers may do so during driving C/AV or during a subsequent manual driving following experiencing driving in automated mode (Hoedemaeker & Brookhuis, 1998; Skottke et al., 2014; Bianchi Piccinini et al., 2014).

Considering the transition period when both C/AVs and MVs will be present on our road network, it is crucial to understand how they interact in a mixed environment when CAVs are clustered in platoons, and whether the behaviour of MV drivers is influenced by CAV platoons. Very few driving simulator studies to date have focused on the behavioural adaptation of MV drivers when driving next to CAV platoons (see Table 2-8). These studies suggest that MV drivers adapt their behaviour and accept shorter THWs when being in the vicinity of CAV platoons, and this is more significant when the exposure time and conspicuity of the platoons (i.e. larger vehicles such as trucks) increase (Gouy et al., 2013; Gouy et al., 2014; Yang et al., 2019). However, in the driving simulator studies mentioned above, the baseline scenario (when the ego vehicle followed the lead vehicle without the presence of CAV platoons) did not include other vehicles other than the lead vehicle. So, the participant might be less motivated to keep a closer distance to the lead vehicle which leads to a greater difference between the THW in the baseline scenario and the scenario with CAV platoons. Besides, platoon size was selected unrealistically (10-20 platooned vehicles) to cover the entire field of view of the MV driver. So, further research is needed to reveal the reasons behind this behavioural adaptation and to investigate to what extent this behavioural adaptation would occur under actual driving and platooning conditions.

Table 2-8 Summary of literature in behavioural adaptation of MV drivers

Authors	Tools and scenario description	Impacts Found
(Gouy et al,. 2013)	**Driving simulator:** Participants followed a lead vehicle in the following scenarios: - Baseline scenario with no CAV - Platoons of 20 CAVs were present with THW=0.3s - Platoons of 20 CAVs were present with THW=1s	- No change in preferred THW of participants - The mean THW was higher in baseline - Only a small difference in THW kept by participants when driving next to platoons keeping THW of 0.3s compared to 1s - In platoon conditions and especially in THW0.3s drivers were very close in average to the limit of preferred THW.
(Gouy et al,. 2014)	**Driving simulator:** Participants followed a lead vehicle in the following scenarios: - Baseline scenario with no CAV - Platoons of 10 trucks were present with THW=0.3s - Platoons of 4 trucks were present with THW=1.4s	- Participants maintained on average a smaller THW in scenario 2 than in scenario 3. - No significant difference due to the THW order (short-large vs large short) - The mean of minimum THWs was smaller in scenario 2 than in scenario 3 - The standard deviation of lateral position was shorter in than THW1.4s
Yang et al. (2019)	**Driving simulator:** Participants followed a lead vehicle in the following scenarios: 1. Baseline scenario with no CAV 2. CAV platoons were present with THW=0.5s mixed with MVs 3. CAV platoons were present with THW of 0.5s on DLs with: a) continuous access, b) limited access with buffer c) limited access with barrier	- Scenario 3(c) could have a positive impact on behavioural adaptation of MV drivers

On the other hand, separating the CAV platoons from manual traffic via DLs could potentially reduce the indirect behavioural adaptation of MV drivers (Yang et al., 2019). However, the impacts of DLs on MV drivers' behavioural adaptation might be dependent on the penetration rates of C/AVs and DL design and utilization policies. These aspects have not been yet thoroughly investigated. Moreover, there is a clear knowledge gap regarding the performance and safety implications of different design configurations of road sections with DLs on transient manoeuvres (merging, splitting, switching from manual to automated control, entry and exit of DLs), and the impact of different lane utilization policies on the behaviour of drivers, and as a result on traffic performance and traffic safety.

Behavioural adaptation regarding C/AV drivers while driving in automated mode has been also studied (summarized in Table 2-9). Hoedemaeker and Brookhuis (1998) conducted a driving simulator study and found that AV drivers adapt their behaviour when driving in ACC mode reflected in higher speeds and smaller minimum THWs. Drivers also accepted shorter gaps and higher manoeuvre velocity when merging into a busy lane. The authors also found that when drivers had to perform an emergency stop while driving in a traffic queue, they had to brake harder with ACC. Similarly, Balk et al. (2016) examined driver's merging behaviour into a CACC dedicated lane when driving an MV, a CACC vehicle with merging assistant, and a CACC vehicle without merging assistant. The drivers of a CACC vehicle with merging assistant accepted shorter gaps when merging into the CACC dedicated lane. This raises the question: will this behavioural adaptation remain persistent in the next manual drive as some earlier studies showed the carry-over effects of automated driving (Skottke et al., 2014; Miller and Boyle, 2019)? How would this affect the behaviour of MV drivers?

Table 2-9 Summary of literature in behavioural adaptation of C/AV drivers

Authors	Tools and scenario description	Impacts Found
Hoedemaeker & Brookhuis (1998)	Driving simulator: Four groups of drivers with different driving style concerning speed and focus followed a lead while: – No other vehicle was present – ACC was deactivated – ACC was over-rulable with preferred THW, THW=1s, THW=1.5s – ACC was not over-rulable with preferred THW, THW=1s, THW=1.5s	a) all groups chose higher speed when driving with ACC b) The SDLP[1] was increased when driving with ACC c) subjects accepted shorter gaps and higher manoeuvre velocity when merging into a busy lane.
Nowakowski et al. (2011)	Field operational test: Participants completed the following drives: – First baseline, one day of (Non-ACC) Driving – Six days of ACC Driving – Second Baseline, one day of (Non-ACC) Driving – Three days of ACC Driving – Two days of CACC driving following a lead vehicle	– Male drivers spend more time keeping short THWs compared to females (not significantly) – Drivers chose 50% shorter THWs in CACC mode compared to ACC (authors had some reservations about this since following events lasted very shortly)
Kessler et al. (2012)	Field operational test: Participants drove a vehicle with ACC together with forward collision warning (FCW) for a duration of 12 months in following conditions: – Baseline scenario without ACC and FCW – Treatment scenario when drivers could use ACC+FCW whenever they need	1. THW increased by 16% using ACC 2. number of incidents decreased by 80% with ACC 3. number of THWs lower than 0.5s decreased by 73% 3. drivers chose higher speeds (2%) with ACC 4. higher speed was due to ACC as well as drivers' choice of when to use ACC
Bianchi Piccinini et al. (2014)	Driving simulator: Two groups of drivers with and without ACC experience drove on a real motorway: – with ACC – without ACC	a) both groups drove with slightly lower speed when in ACC mode b) ACC drivers drove faster than regular drivers c) compared to regular drivers, ACC drivers spent more time under critical value when driving without ACC d) behavioural adaptation did not lead to unsafe driving
Skottke et al. (2014)	Driving simulator: – The first group of drivers performed three sections of driving: o pre-automation (manual drive), o automation (ACC, THW=0.3s and heading control), o post-automation (manual drive). – The second group performed o manual drive all through the experiment.	– THW decreased and SDLP increased after switching from automated to manual drive – The increase in SDLP is caused as a result of distraction and inattentiveness after a long drive in the driving simulator – Reduction in the THW was attributed to the automated drive which lasted up to 10 km after leaving the automation
Miller et al. (2019)	Driving simulator: – Participants completed the following drives: o Day 1: 2 manual drive and 1 automated drive (lane keeping system), o Day 2: 2 automated drive (lane keeping system) o Day 3: 2 manual drive and 1 automated drive (lane keeping system), – A control group (driving manually) was used to measure baseline changes in performance.	– Participants had an increase in lateral deviation after the lane keeping system was removed – Participants had shorter mean TTC both during exposure and after the automation

1: standard deviation of lateral position

Bianchi Piccinini et al. (2014) investigated the behavioural adaptation in ACC mode for drivers with and without ACC experience. The authors suggested that drivers adopt slightly lower driving speeds and larger time headways when using the ACC system. Drivers with ACC experience drove faster than regular drivers and maintained smaller headways when in ACC mode which could be an effect of indirect behavioural adaptation or a carryover effect of driving with the ACC system.

Kessler et al. (2012) conducted a large scale field operational test and examined drivers' behavioural changes when using ACC together with forward collision warning. They calculated average THW and speed as an indicator for safety and efficiency, respectively. As a result, THW increased by 16% when using the system which consequently decreased the frequency of harsh braking. Similarly, the number of incidents decreased by 80% based on vehicle kinematics. In terms of speed, in line with Hoedemaeker & Brookhuis (1998), drivers chose higher speeds with the system active both in urban and rural roads. The authors suggest that the increase in speed could be interpreted both as a result of behavioural adaptation to the system, as well as drivers' choice of when to use the system. Because drivers were more likely to use the system when the situation allowed for a higher speed.

One important issue to note in designing DLs is to consider the carry-over effects of automated driving. When exiting the DLs, drivers need to switch off the automation and take control of the vehicle, depending on the lane utilization policy or their own decision on how to drive on normal lanes. Studies have found that behavioural adaptation lingers during the subsequent manual drive after experiencing automation (Skottke et al., 2014; Miller & Boyle, 2019). This is important to note in designing the exit areas of DLs. Transition lanes may be needed to give the drivers enough time to get back in the loop and regain control of the vehicle. Further investigation is needed to find out how long this behavioural adaptation persists. This gives the designers insights about the length of the possible transition lanes.

Regarding choosing the THW when driving in C/ACC mode, Nowakowski et al. (2011) revealed in a field study that male drivers spend more time keeping short THWs compared to females. However, this was not statistically significant. Besides, drivers chose around 50% shorter THWs in CACC mode compared to ACC. The authors had some reservations about this conclusion since the following events mostly lasted less than a minute and only half of them took two to three minutes. Thus, further investigation is needed regarding drivers' preferences in choosing C/ACC system settings as well as driver characteristics such as age, gender, and driving style on these preferences in a mixed and DL scenario.

In summary, there is limited research regarding the behavioural adaptation of human drivers when driving next to AVs and CAVs and lack of knowledge regarding the reasons behind this behavioural adaptation and the extent to which it is considerable. Also, the role of driver's characteristics on this phenomenon is not fully studied for C/AV drivers and is lagged behind for MV drivers.

2.4.2.2 Control transition

In some traffic situations, human drivers may prefer to take control of the vehicle and switch off the automation mode (driver-initiated driver in control) or switch it on (driver-initiated automation in control). Depending on the level of automation, it is also possible that the system requests from the driver to take control because of its functioning limitations (automation-initiated driver in control), or the system takes the initiative to take control of the vehicle to prevent a dangerous situation (automation-initiated automation in control). These changes from automated to manual mode and vice-versa are called transitions of control (Lu & de Winter, 2015), which may affect the dynamics of vehicles (Varotto et al., 2015). Several studies have focused on the transitions to manual control in critical situations (take-over request) and have investigated the factors influencing the takeover time and post-takeover control (see the review by McDonald et al. (2019)).

Table 2-10 Summary of literature in driver-initiated driver in control transitions

Authors	Tools and scenario description	Impacts Found
Viti et al. (2008)	**field operational test:** - Twenty drivers drove an ACC vehicle for a period of 6 months. - The braking behaviour during and one second after the deactivation of ACC was recorded. - ACC deactivated when driving with a speed below 30 km/h	- drivers deactivate ACC in dense traffic situations (20 to 40 km/h/lane) - Since drivers rarely braked hard after deactivation of ACC, it was concluded that deactivation is not because of limitations in the functionality of ACC or an emergency situation
Pereira et al. (2015)	**field operational test:** Participants drove vehicles equipped with Stop & Go ACC which stayed active in speeds below 30 km/h in urban roads and motorways	- on urban roads, drivers are more likely to switch to manual mode in situations that are impossible to handle by the ACC system - on motorways, drivers used the manual mode to change lane or exit the main road.
Varotto et al. (2017)	**field operational test:** Participants drove an ACC vehicle on a freeway section including on- and off-ramps during peak hours. Participants were instructed to select their desired THW including 1.0, 1.4, 1.8, and 2.2 s	Drivers are more inclined to deactivate the system when: - approaching a slower leader - driving above the ACC target speed - expecting vehicles cutting in - before exiting the freeway

Since the aim of this study is to get insights about the relations between driver behaviour and DL design, our focus is mostly on drivers' decisions in engaging or disengaging the automated mode. So, the driver-initiated transitions are reviewed in this paper. Table 2-10 summarizes the studies which were conducted to identify the main factors influencing drivers' decisions in driver-initiated driver in control transitions. On the one hand, Viti et al. (2008) concluded that drivers switch off the ACC because their expectations are not met, and not because of the limitations in the functionality of the ACC or an emergency situation. On the other hand, Pereira, Beggiato & Petzoldt (2015) showed that drivers are more likely to switch to manual mode in situations that are impossible to handle by the ACC system. For instance, stopping at a traffic light while there is no vehicle in front of them and when approaching a standstill vehicle. The differences in the findings of these studies could be due to the differences in the specifications of the ACC systems used in the experiments. For example, in the study of Viti et al. (2008) the ACC automatically deactivated when driving with a speed below 30 km/h which could happen in dense traffic situations. In case the drivers anticipated this, they switched off the ACC system and counted on their own driving performance to avoid an emergency request by the vehicle. While in the study of Pereira et al. (2015) they used a vehicle equipped with Stop & Go ACC which stayed active in speeds below 30 km/h. Varotto et al. (2017) revealed that drivers are more inclined to deactivate the system when approaching a slower leader, when driving above the ACC target speed, when expecting vehicles cutting in, and before exiting the freeway. However, if drivers' acceptance of the system is high, they would prefer to conduct the lane changing manoeuvre in automated mode if this feature is available (Madigan et al., 2018).

Moreover, some drivers are more likely to resume manual control compared to others which emphasizes the need for research on the influence of drivers' characteristics on control transitions (Varotto et al., 2017).

As it can be seen in Table 2-11, only a few driving simulator experiment studies investigated the time it takes the drivers to get back to automated mode after the automation is available again namely driver-initiated automation in control (Eriksson & Stanton, 2017; Varotto et al., 2015). As the authors explain it, the different reported ranges for the time drivers take to relinquish control to automation, could stem from different instructions given to the participants. Further research is needed to study the reasons and motivations behind these transitions of control under different road and traffic conditions and the resulting time needed to switch back to automation mode. The time range to get back to automated mode could be different when getting back to automation after an emergency request to take back control (automation-initiated-driver in control), or getting back to automation after driver-initiated-driver in control.

In summary, control transitions have been mainly studied regarding ACC equipped vehicles and not CACC equipped ones, with a focus on driver-initiated driver in control. The factors influencing driver's decisions in driver-initiated driver in control transitions are not known yet. Regarding the transitions to automated mode, few studies have investigated the time it takes to switch to the automated mode from the manual (driver-initiated automation control). However, to the best of our knowledge, factors encouraging drivers to switch back to automated mode are not studied yet. In the case of DLs, it is relevant to investigate if drivers are more willing to switch to automated mode (if the feature is available) when entering a lane which is exclusively dedicated to C/AVs (Eriksson and Stanton, 2017). Furthermore, it can be hypothesized that human drivers may behave differently in terms of control transitions when driving in such a lane rather than in a mixed traffic situation. Finally, the impacts of long-term experience of using C/ACC on control transitions have not been yet understood.

Table 2-11 Summary of literature in driver-initiated automation in control transitions

Authors	Tools and scenario description	Impacts Found
Varotto et al. (2015)	Driving simulator study: Participants drove an ACC equipped vehicle. At a specific location, a sensor failure was simulated and the drivers were expected to resume manual control. After a while, the system notified the drivers that automation is available again and they could voluntarily switch on the automation.	- The median time to resume control after a sensor failure was 3.85 s. - The median time until ACC was voluntarily switched on after the message was equal to 5.80 s.
Eriksson et al. (2017)	Driving simulator study: Twenty six participants drove a highly automated vehicle and the system prompted them to either resume control from or relinquish control to the automated driving system. While they were engaged in a secondary task in some scenarios.	- The time it takes to resume manual control from automated mode was calculated as: ○ 4.46 ± 1.63 s when not engaged in a secondary task ○ 6.06 ± 2.39 s when engaged in a secondary task - The time it takes to switch to the automated mode from manual ranges from 2.8 to 23.8 s and no significant difference was found when engaging in a secondary task.

2.5 Research agenda

Based on the review and the identified research gaps in the literature, the conceptual framework is presented again in Figure 2-3, with modified arrows to illustrate the relations which were studied (bold solid arrows), those that are understudied (solid arrows), and those that are not yet addressed in the scientific literature (dashed arrows). Each arrow was given a number to facilitate the discussion that follows.

As conceptualized in Figure 2-3, there are many relationships between the different aspects which need to be considered for the design and operation of DLs. In the following sub-sections, these relations are further explained and a motivation for their research status is given.

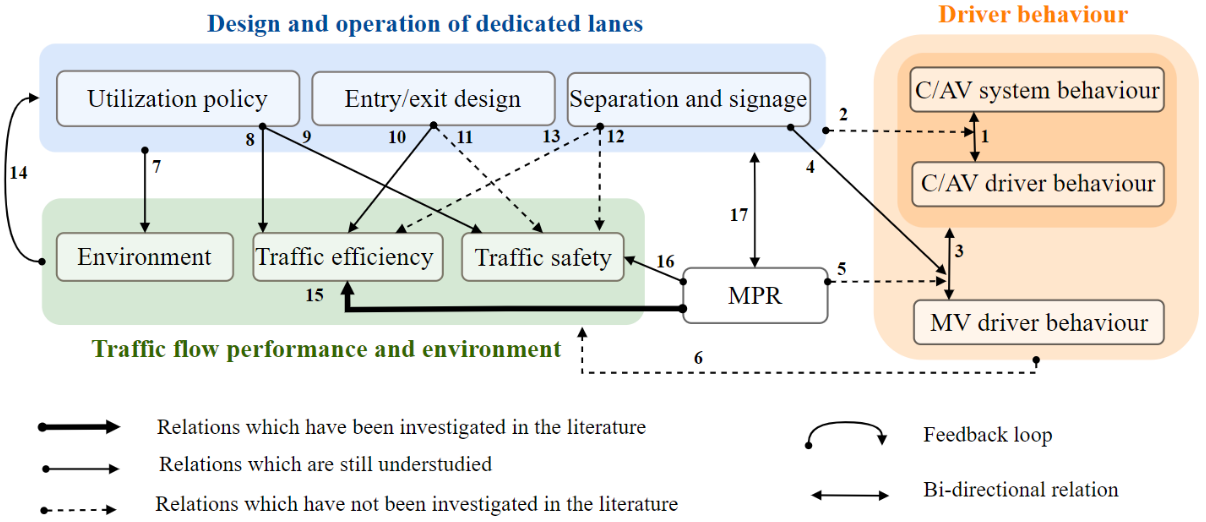


Figure 2-3 Conceptual framework for the relations between the design and operation of dedicated lanes, driver behaviour, traffic flow performance and the environment.

2.5.1 Impacts of DLs on driver behaviour

As illustrated in the conceptual framework, C/AV drivers occasionally need to interact with the C/AV system. These interactions could involve control transitions and behavioural adaptation of C/AV drivers **(arrow 1)**. Regarding control transitions, research has investigated the important factors behind drivers' decisions in driver-initiated driver in control transitions. While driver-initiated automation in control transitions has merely been the focus of the literature to date. This could have implications for designing DLs. In other words, if drivers are not willing to enter a DL in an automated mode, then there might be a need for a designated area at the entrance of the DL to allow manual driving temporarily after merging to this lane (given that DLs are for the exclusive use of AVs). C/AV drivers also adapt their behaviour to behaviour of the system (i.e. shorter THW) when driving in automated mode **(arrow 1)**. This behavioural adaptation may be persistent during the subsequent manual drive as well (carry-over effect). Available literature in this area is mostly focused on the longitudinal manoeuvres such as THW in car following. The impacts of automation of lateral control on behavioural adaptations in transient manoeuvres (merging, splitting, switching from manual to automated control, entry and exit of DLs) is not yet completely understood. A relevant question which arises here is: what would be the impacts of DLs configurations (utilisation policy, entry/exit design, separation) on C/AV driver, C/AV system performance, and the interaction between them **(arrow 2)**?

Performance of C/AVs could be influenced by MVs (i.e. splitting the platoons by merging in between platoons) **(arrow 3)**, and the other way around, MV drivers adapt their car following behaviour when driving next to CAV platoons as has been shown in few driving simulator studies **(arrow 3)**. However, the reason behind this behavioural adaptation and the extent to which it has a significant impact on traffic efficiency and safety under actual driving conditions is not yet well understood. Furthermore, research is needed to investigate if a hard separation (i.e. guardrails or concrete barriers) could influence this behavioural adaptation **(arrow 4)**.

In addition, the extent of MV drivers' behavioural adaptation as the MPR of C/AVs increases still needs to be investigated. Thus, research on the short and long-term impacts of MPR of C/AVs on the behavioural adaptation of MV drivers is recommended **(arrow 5)**.

Obviously, changes in the driver behaviour could have implications on traffic flow performance which emphasizes the need to understand the impacts of DL design configurations on driver behaviour and consequently investigate its implications on traffic flow performance including safety and efficiency **(arrow 6)**.

2.5.2 Impacts of DLs on traffic flow performance and the environment

Despite the large body of research which has introduced design concepts for DLs, few studies to date have evaluated the environmental impacts of implementing these lanes **(arrow 7)**. Regarding the use of DLs, research so far has investigated the impacts of different utilization policies on traffic efficiency **(arrows 8)** and traffic safety **(arrow 9)**, while only considering the longitudinal automation. According to the literature, mandatory use of C/AVs leads to an increase in the congestion and shockwave formation due to the high intensity of lane changes towards DLs. Obviously, this is unlikely to happen in the presence of dedicated on- and off-ramps to DLs. Also, automated merging, taking into account the connectivity between vehicles could probably avoid this problem since lane changing towards DLs and merging into platoons on DLs would be better synchronized.

When it comes to entry/exit configurations (above/below-grade limited, at-grade limited, and continuous access), studies have investigated the efficiency implications **(arrow 10)** of at-grade continuous and limited access to DLs without a focus on the exact length of access areas and the proximity to the nearest on- or off-ramps. Above/below-grade limited access type is expected to perform better than at-grade access type. However, traffic flow simulation studies are needed to investigate to what extent this improvement is considerable and whether or not the reduced cost of congestion can compensate for the construction costs. Investigating the safety impacts of each access type could also play an important role in selecting the final configuration for implementation **(arrow 11)**.

It is recommended by the early research on Automated Highway System, to have barriers or buffers between automated and manual traffic for safety reasons. However, there is limited evidence-based knowledge regarding the benefits of each separation type for traffic flow performance measures: safety **(arrow 12)** and efficiency **(arrow 13)**. It is clear that traffic flow performance measures could be used as a feedback for reconsideration of the design and operation of DLs **(arrow 14)**.

Considering the growth in MPR of C/AVs, studies have concluded that higher MPRs lead to improved traffic efficiency **(arrow 15)**. However, the impact of increasing MPR on traffic safety is still understudied **(arrow 16)**. In addition, further research is needed to define suitable design configurations of DLs for different MPRs **(arrow 17)**. And the other way around, further research is needed to understand the implications of DLs on MPR: Will people be more inclined to purchase C/AVs and use automation functionalities if DLs are implemented? **(arrow 17)**?

2.5.3 Challenges on design and operation of dedicated lanes

The challenge in defining dedicated lane design configurations is to specify the types of vehicles with certain capabilities to be allowed on these lanes. Depending on the type of vehicles, a certain level of digitalization/intelligence may be required from the infrastructure which can be offered by different levels of infrastructure according to ISA levels (Anna Carreras et al., 2018). These specifications could vary depending on different MPRs of C/AVs. Based on the availability of space and funding, the decision on adding a lane or dedicating an already existing lane to C/AVs could be made. This lane should be designed or modified according to the capabilities of the certain types of vehicles allowed to use it. It is crucial to provide clear and comprehensible signage and demarcations to inform both MVs and C/AVs about such a lane. This has merely been the focus of studies in this area. To prioritize the research needs the methodological and research challenges are described in the following sections.

2.5.3.1 Methodological challenges

Understandably, impacts of the proposed lane modifications on traffic safety and efficiency have been mostly investigated to date by traffic flow simulations. Thus, the challenge is to change and adapt the current behavioural models in the simulation to reflect as realistically as possible the behaviour of the different types of vehicles (MVs, AVs, and CAVs), their capabilities and their interactions. One possible approach to accomplish this is by implementing the empirical data collected from existing field tests and also incorporating the insights from driving simulator studies regarding human factors (i.e. behavioural adaptation of human drivers when interacting with C/AVs) to traffic flow simulation models (Calvert, Wilmink and Farah, 2017). So, prior to the evaluation of the performance of DLs, we need to understand the behaviour of different road users (AVs, CAVs, MVs) when interacting with each other conducting driving simulator experiments and field tests when possible. To the best of our knowledge, the impacts of implementing DLs on traffic efficiency and safety have been so far studied taking into account the connectivity and automation of the longitudinal control (i.e. CACC) while the connectivity and automation in transient manoeuvres (i.e. automated merging or lane changing assistance) have rarely been considered. Therefore, the challenge here is to develop automated lane change algorithms taking into account connectivity between CAVs and possibly also between CAVs and MVs for future traffic simulation studies. To further enhance the validity of those experiments existing algorithms of AVs and CAVs, as developed by the automotive industry, need to be incorporated in driving simulator experiments and traffic flow simulation.

2.5.3.2 Research related challenges

The main research related challenge is to explore the combined effects on traffic safety and efficiency of DLs while considering driver behaviour adaptation and control transitions between manual and automated operation. Some studies have assessed the effects of the increase in MPR on traffic efficiency when DLs are implemented, leading to the conclusion that at a certain MPR, DLs start to improve the traffic performance. However, studies on transitions of control suggest that drivers do not use automation mode in some situations. Thus, MPR alone may not reflect the adoption rate of the C/AVs. This shows how a wrong conclusion could be drawn in the absence of important factors.

2.6 Conclusions and recommendations

The main contribution of this paper is the identification of the knowledge gaps regarding the design and operation of dedicated lanes for connected and automated vehicles on motorways and the potential implications on traffic performance and safety. The literature on this topic is still in its early stages, and no single study gives more than a fragment of the total picture. These results were summarized in a conceptual framework providing insights into the relationships and contributing factors which need to be considered for the design and implementation of dedicated lanes and their research status.

Based on the conceptual framework and the identified knowledge gaps an agenda for research is proposed. More specifically the research agenda emphasizes the need for specifying the vehicle types (i.e. automation functionalities) to be allowed on dedicated lanes, the need for understating the behavioural adaptation of MV and C/AV drivers considering the impacts of different MPRs, and the importance of demarcations and signage. Methodological challenges include the complexity of carrying out a large scale field test of C/AVs and MVs on dedicated lanes, and thus the need to rely on driving simulator and simulation studies which would require defining more realistically the behavioural models, as well as considering automation and connectivity in transient manoeuvres in traffic simulation models. Therefore, a hybrid research approach will be needed combining the strengths of the different research methodologies to compensate for their weaknesses when used separately.

Chapter 3

The Impact of a Dedicated Lane for Connected and Automated Vehicles on the Behaviour of Drivers of Manual Vehicles

Based on the research agenda proposed in the previous chapter, research is needed to investigate the behavioural adaptation of MV drivers in both lateral and longitudinal manoeuvres while driving in a mixed traffic with CAVs. Also, studying the impacts of a DL on this behavioural adaptation is recommended. Thus, this chapter addresses these research gaps by conducting a driving simulator study to investigate the behavioural adaptation of MV drivers in car-following and lane changing when they drive next to a DL and compares that to a mixed traffic situation.

This chapter is based on the journal publication: **Razmi Rad, S.**, Farah, H., Taale, H., van Arem, B., Hoogendoorn, S.P., 2021. The impact of a dedicated lane for connected and automated vehicles on the behaviour of drivers of manual vehicles. Transp. Res. Part F Traffic Psychol. Behav. 82, 141–153. https://doi.org/10.1016/J.TRF.2021.08.010

3.1 Introduction

Connected and automated vehicles (CAVs) are expected to enhance the traffic efficiency by driving with shorter time headways and the traffic safety by shorter reaction times (Daniel J. Fagnant and Kockelman, 2015). However, one of the main concerns regarding their deployment is the mixed traffic situation, in which CAVs and manually driven vehicles (MVs) share the same road. A key research gap in this respect is whether MV drivers would interact differently with CAVs compared to their interaction with other MVs (Razmi Rad et al., 2020a).

A field study by Rahmati et al. (2019) suggests that there is a statistically significant difference between human drivers' behaviour when following an automated vehicle compared to an MV. Participants were asked to perform two drives in platoons of three vehicles. The participants always drove the last vehicle in the platoon, following an automated vehicle (scenario A) or an MV (scenario B). The lead vehicle was an automated vehicle following a series of speed profiles extracted from the Next Generation Simulation dataset, NGSIM (US Department of Transportation – FHWA, 2007). Based on the results, MV drivers felt more comfortable following an automated vehicle and drove closer to their leader if they followed an automated vehicle, compared to following an MV.

Driving simulator experiments have studied the interaction between MVs and CAVs in a mixed traffic situation (Gouy et al., 2013; Gouy et al., 2014; Schoenmakers, Yang, & Farah, 2021). Gouy et al. (2013) tested the car-following behaviour of MV drivers in the presence of CAV platoons in a driving simulator experiment to investigate if there is any behavioural adaptation in the car-following behaviour of MV drivers. In this study, participants drove an MV and followed a lead vehicle in the vicinity of CAV platoons keeping long (1s) or short (0.3s) time headways (THWs). They found that MV drivers drove very close to, but not under their minimum preferred THW in the scenario with CAV platoons specially when CAVs kept short THW.

In a later study, Gouy et al. (2014) studied the behavioural adaptation of MV drivers in car-following, this time with higher exposure time to CAV platoons and higher conspicuity of the platoons by using trucks instead of personal vehicles. Platoons of trucks kept long (1.4s) or short (0.3s) THWs. According to the results, MV drivers imitated the truck platoons' behaviour by keeping significantly shorter THWs and also spent more time keeping a THW below a safety threshold of 1s. The results suggest that there can be negative behavioural adaptation when humans drive next to CAVs, especially when the exposure time and conspicuity of platoons are increased. However, the authors reported that this behavioural adaptation is not long lasting since there were no carryover effect from platoon condition with THW of 0.3s to the other one (1.4s).

Dedicating a lane to CAVs is suggested in the literature to overcome the difficulties with the mixed traffic situation (Kockelman et al., 2016; Shladover, 2005; Lumiaho & Malin, 2016; McDonald & Rodier, 2015; Milakis et al., 2015). However, the implications of implementing such a lane is still understudied (Razmi Rad et al., 2020a). Schoenmakers et al. (2021) hypothesized that drivers will adapt their driving behaviour when driving in proximity to a platoon of CAVs on a dedicated lane by reducing their THW and that this effect would be different for different types of separations. They conducted a driving simulator study to test this hypothesis. Participants were assigned to a car-following task in four different scenarios: a) Baseline with no CAVs, b) CAVs drove on continuous access dedicated lane, (c) CAVs drove on a limited access dedicated lane with buffer, and (d) CAVs drove on a limited access dedicated lane with barrier. The results show that compared to the baseline scenario with no CAVs, MV drivers drove with a significantly lower THW from the lead vehicle when driving on the lane adjacent to the continuous access dedicated lane and limited access dedicated lane with buffer. However, MV drivers' THWs were only marginally different in the scenario with limited access dedicated lane with barrier compared to the baseline. In fact, the barrier partially blocked the view of MV drivers towards the CAV platoons and consequently (partially) prevented the behavioural adaptation. Although barrier separated DL was shown to be the safest scenario considering the car following THW, implementing such barriers would be expensive and counterproductive for the flexibility of the road system. Moreover, more crashes happen near the beginning of highway sections with barrier compared to the sections without barrier (Tsao et al., 1995).

Dedicating an existing highway lane to CAVs implies restricting MVs from using one lane of the motorway which could significantly increase their travel time if the actual share of CAVs in traffic or market penetration rate (MPR) of CAVs is lower than the lane saturation level (Ivanchev et al., 2017; Van Arem, Van Driel, Visser, 2006). So, exploiting the beneficial implications of a DL would only be possible when we reach to moderate MPRs around 30-50% (Ivanchev et al., 2017; Van Arem, Van Driel, Visser, 2006; Vander Laan & Sadabadi, 2017; Xiao, Wang, & Van Arem, 2020; Madadi, Van Nes, Snelder, & Van Arem, 2021). This raises the question as to how would be the behavioural adaptation of MV drivers at moderate MPRs of CAVs just before we can implement a DL.

Moreover, the extent of the behavioural adaptation might be different for different drivers. Driver characteristics and driving styles may influence driving behaviour. Studies in the literature suggest that drivers with different self-reported driving styles show different behaviour when driving. Taubman-Ben-Ari et al. compared the scores of four broad driving styles measured by the Multidimensional Driving Style Inventory (MDSI) with the naturalistic driving recorded by an in-vehicle data recorder. They found that risky behaviours measured by the in-vehicle data recorder positively correlate with high MDSI scores on the risky and hostile driving styles and negatively correlate with high MDSI scores on the anxious and careful driving styles (Taubman - Ben-Ari et al., 2016). In another driving simulator study, Farah et al. found a correlation between the MDSI score for the hostile driving style and overtaking accepted gaps and driving speeds (Farah et al., 2009).

Furthermore, age and gender of drivers play important roles in driving behaviours (Rajalin, Hassel, & Summala, 1997; Farah, 2011; Bener & Crundall, 2008). According to the literature, young, male drivers are more likely to follow a lead vehicle more closely (Rajalin et al., 1997), overtake while accepting shorter gaps (Farah, 2011), and perform risky manoeuvres (Bener and Crundall, 2008). Schoenmakers et al. also studied the relationships between car-following and sociodemographic variables reported in a questionnaire by participants. According to the results, the average THW and its standard deviation were distinctly lower in males than females (Schoenmakers et al., 2021). Given these results it is relevant to investigate the behaviour of different groups of drivers (age, gender, and driving style) when driving next to CAVs.

Previous research has suggested that MV drivers drive closer to their leaders when driving next to CAV platoons keeping short THWs (Gouy et al., 2013; Gouy et al., 2014; Schoenmakers et al., 2021). It is suggested by these studies that the behavioural adaptation is more significant when the exposure time and conspicuity of the platoons (i.e., larger vehicles such as trucks) increase. However, these studies assumed very large platoons, representative of high MPR in situations that there is no limitation for platoon size which is a quite unlikely scenario. Moreover, most of these studies focused on the longitudinal driving behaviour and did not consider behavioural adaptation in lateral manoeuvres. Further research is therefore needed to firstly examine this behavioural adaptation in both the longitudinal and lateral dynamics; Secondly, to investigate if the behavioural adaptation happens at moderate MPRs before implementing DLs; and thirdly, to investigate the relationship between this behavioural adaptation and driving style and characteristics of MV drivers.

Therefore, the main objective of this study is to investigate the behavioural adaptation of MV drivers in car-following and lane changing when driving adjacent to the DL and compare that to the behavioural adaptation when driving in a mixed traffic flow at a moderate MPR. It should be noted that, in this paper, CAVs refer to connected and automated vehicles which are able to drive in platoons keeping short THWs (0.3s), which corresponds to SAE levels 4 and 5 (SAE, 2018).

The main expectations are:

i. In a mixed traffic situation and at moderate MPRs (43% in this study) of CAVs the behavioural adaptation of MV drivers is negligible due to lower exposure time and scarce platoons (Expectation 1).
ii. MV drivers adapt shorter time headways (Expectation 2a) and merging gaps (Expectation 2b) in car-following and lane changing respectively when driving next to CAV platoons concentrated on one lane.
iii. This behavioural adaptation is different for drivers with different demographics and driving styles (Expectation 3).

To test the aforementioned expectations and given the difficulty in doing on-road experiments with CAVs, a driving simulator experiment was developed using a medium fidelity driving simulator.

The rest of the paper is structured as follows. In Section 3.2 the method, the experimental setup and scenario details are described following the data collection and processing and analysis approach. The results are provided in Section 3.3, followed by the discussion in Section 3.4. Finally, Section 3.5 provides the main conclusions and formulates recommendations for further research.

3.2 Methodology

The following sub-sections explain the recruitment of participants for the driving simulator experiment, the apparatus set-up, the driving simulator scenarios, the questionnaires used, and finally the experiment procedure.

3.2.1 Participants

A total of 51 participants (22 females, 29 males) took part in the experiment. They were recruited via a panel provider company based in the Netherlands and an advertisement on the TU Delft campus (Delft, The Netherlands). All participants held a valid driver's license and had experience driving on the Dutch freeways. Their age and gender distribution is illustrated in Figure 3-1.

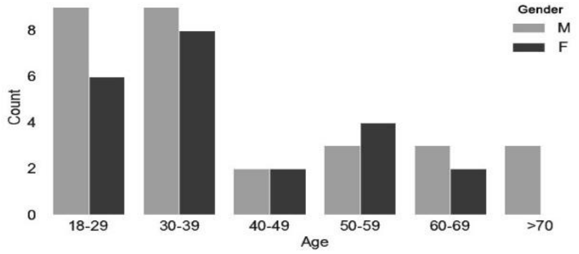


Figure 3-1 Age and Gender distribution of participants.

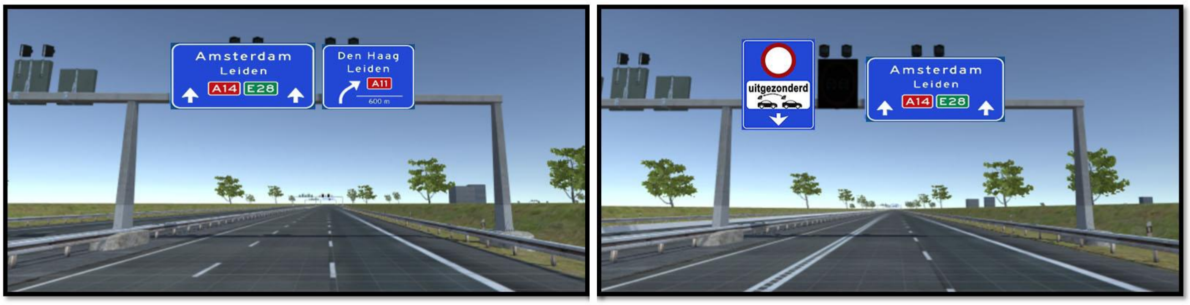
3.2.2 Apparatus

The study was conducted in a fixed-based driving simulator comprised of a dashboard mock-up with three 4K high resolution screens, providing approximately a 180-degree vision, Fanatec steering wheel, pedals and a blinker control (Figure 3-2).

Figure 3-2 The fixed-based driving simulator.

3.2.3 Design of the driving environment

The simulated road environment consisted of a typical three-lane Dutch motorway. A double crash barrier separated the two carriageways and a single crash barrier was present on both sides of the motorway. The speed limit was set to 100 KPH according to the Dutch regulations regarding daytime speed limits. The route included three stretches of motorway which were connected to each other with on- and off-ramps via large curves. The traffic flows were equal per lane in all scenarios. Three scenarios were designed as follows:



(a) (b)

Figure 3-3 Driving environment, (a) Base and Mixed scenario, (b) Dedicated lane scenario.

Base: all vehicles were manual in this scenario, keeping THWs in the range of 2 to 4 seconds. Vehicles on the right lane were slower than others to motivate the participant to change lanes towards faster lanes given that one of the objectives of this study was to measure accepted gaps when changing lanes. The signage and demarcations of the driving environment was designed according to what drivers experience on a typical Dutch motorway (see Figure 3-3(a)).

Mixed: this scenario contained both MVs and CAVs in a mixed driving situation. The MPR of CAVs was set to 43% and they could drive on any lane of the motorway in platoons of 2 to 3 vehicles. The intra-platoon and inter-platoon THWs were set to 0.3s and 2s, respectively. The signage and demarcation of the motorway did not differ with that of the Base scenario (Figure 3-3 (a)).

Dedicated lane: The left most lane of the motorway was dedicated to CAVs and therefore, CAVs were not allowed to drive on the other lanes. Intra-platoon and inter-platoon THWs were set to 0.3s and 2s, respectively, similar to the Mixed scenario. Also the platoon size (2 to 3 vehicles) and the MPR were similar as in the Mixed scenario (43%). To inform the participants about the dedicated lane, a buffer demarcation separating the DL and the other lanes was applied. Road signs were also added as illustrated in Figure 3-3(b) to further clarify the purpose of this lane. Participants also read about the DL concept in the instruction before performing the drives.

3.2.4 Road sign for the DL

The road sign contained a "no entry" symbol with an exception (uitgezonderd in Dutch) for CAVs. The platooning pictogram was selected based on results of a survey on symbol comprehension. A total of 455 respondents filled in the survey which consisted of different pictograms. They were asked to write down the meaning of the symbols and take an "educated guess" if they were not sure of the meaning. According to the survey results presented in word clouds, Figure 3-4(c) was the most likely pictogram which was comprehended as CAV platoon. Moreover, in a multiple choice question, respondents were asked to choose a pictogram which could best illustrate CAVs. Pictogram (a) to (d) were selected by 21%, 11%, 44%, and 24% respectively. So, based on these results Figure 3-4(c) was chosen as the CAV pictogram for the DL sign, as can be also seen in Figure 3-3(b).

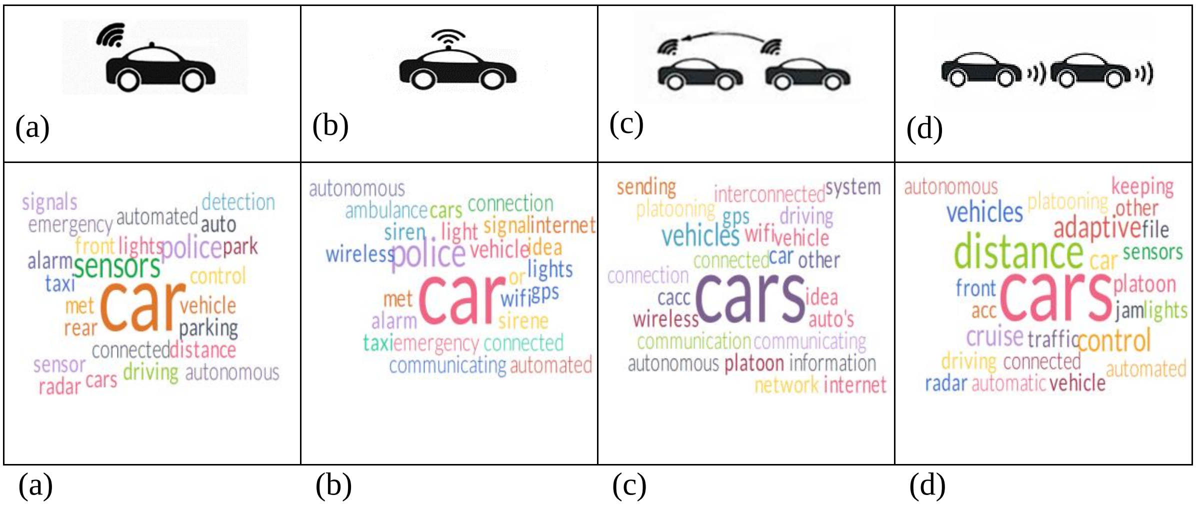


Figure 3-4 Pictograms for the DL sign.

3.2.5 Experimental design and procedure

The experiment consisted of a questionnaire and three consecutive drives in the driving simulator. Before performing the drives, participants were presented with a leaflet explaining their task and the procedure of the experiment as well as the concept of dedicated lanes. The leaflet also mentioned that they should drive as much as possible as they would normally do in real life. They were also advised to stop the experiment if they felt any discomfort (i.e., simulation sickness). Next, participants signed a consent form to allow the usage of their data for the research. The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology.

The participants were asked to start the engine, exit a parking lot, enter the motorway and follow the road signs towards their destination, as was given to them at the beginning of the experiment. The route was exactly the same for all scenarios. However, the surrounding environment, the destination, and the road signs were different to minimize the bias effect of familiarity and drivers' expectation. Before starting each scenario, a sticker mentioning the destination was attached to the dashboard in case the participant needed to recall it.

The base scenario (i.e., all vehicles are manual) was always performed first, while the Mixed and DL scenarios were randomized. The participants could not differentiate between the Base and Mixed scenario as the CAVs were not distinguishable. They were only told that in one of the scenarios all vehicles are manual and in another one there will be CAVs driving on any lane. But, before the DL scenario, participants were informed explicitly that CAV platoons will be present and will only drive on the fast lane which is separated via lane marking. They were also told that they cannot drive on that specific lane.

3.2.6 Questionnaires

The Participants were also asked to fill in a set of questionnaires. The first questionnaire was administered to the participants to obtain information about the participants' demographics and driving styles. The multidimensional driving style inventory questionnaire (MDSI) by Taubman-Ben-Ari, Mikulincer, & Gillath (2004) was used for this purpose. MDSI questionnaire contains statements that should be rated on a 6-point scale (‘‘not at all” to ‘‘very much”). The questionnaire assesses four broad domains of driving style and reveals eight main factors: dissociative driving, anxious driving, risky driving, angry driving, high-velocity driving, distress-reduction driving, patient driving, and careful driving. The participants were asked to complete the MDSI questionnaire beforehand at home and to subscribe for a timeslot to participate in the driving simulator part of this study. In total 182 people filled in the questionnaire out of which, 51 participated in the driving simulator experiment as well.

The second questionnaire was administered after the completion of the driving simulator experiment and measured if participants experienced any discomfort such as nausea, oculomotor discomfort, and disorientation, throughout the experiment while driving using the Simulation Sickness Questionnaire by Kennedy, Lane, Berbaum, & Lilienthal (1993). Participants reported on a 4-point Likert scale from 0 (no) to 3 (severe) about how much they felt affected by each symptom.

Finally, the last questionnaire examined participants' presence during the drives. For this purpose the 19 core items of the Presence Questionnaire was used (Witmer et al., 2005). It includes four factors, namely involvement, visual fidelity, adaptation/immersion, and interface quality which influence user presence during the drives with the driving simulator. The items were rated on a 7-point scale.

3.2.7 Data collection and processing

The driving simulator records vehicles' trajectories and time stamps every 0.02 second (50 frames per second) during the drives. The following variables were collected for the ego vehicle and other agents: speed [m/s], position (x, y, z), headings (direction of movement), and driving lane.

The following driving behaviour characteristics were calculated from the vehicle trajectory raw data:

- **Time headway (THW) in car-following** was calculated as the distance between ego and lead vehicle plus the length of the lead vehicle (headway) [m] divided by the speed of the ego vehicle [m/s] (see Figure 3-5(a)). The car-following event was considered five seconds after the moment when the participant changed lane and ended five seconds before the next lane change. This is to exclude those moments just before a lane change when the driver may get closer to the lead vehicle as a preparation for the lane change, or just after a lane change until the driver adjusts the gap to the car-following situation. In addition, to differentiate the car-following and free flow driving, car-following was defined as when the ego vehicle is following a lead vehicle with THW equal or less than 3 s (Pasanen & Salmivaara, 1993; Highway Capacity Manual, 2010).
- **Time gap in lane changing** was calculated as the sum of the headway [m] divided by the speed of the ego vehicle and distance between ego and lag vehicle (lag gap) [m] divided by the speed of the lag vehicle [m/s]. A lane change gap is calculated the moment when the centre of the ego vehicle passes the lane marking (see Figure 3-5(b)).

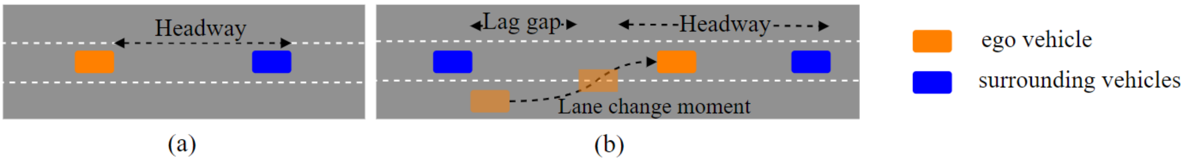


Figure 3-5 (a) Car-following and (b) lane changing parameters.

Four types of lane changes were defined (Figure 3-6):

- **On-ramp**: when the ego vehicle accepts a gap to enter the slow lane from the on-ramp (acceleration lane). In total there were 4 on- ramps in every scenario. The first one was excluded from the analysis since it happened at the beginning of the scenario without being next to any traffic.
- **Off-ramp**: when the ego vehicle accepts a gap in order to change lane from the middle lane to the slow lane to enter the off-ramp (deceleration lane) to exit a section of the highway. This type of lane change happened when the deceleration lane is available and the participant has already seen the road sign showing the destination. In total there were 3 off-ramps in every scenario. However, those participants who kept driving on the slow lane did not have to accept any gap when changing lane to the deceleration lane. As a result, only 45 out of 51 participants have off-ramp gap measurements.
- **Keep right**: when the ego vehicle changes lane to the slow lane after he/she has completed an overtake.
- **Overtake**: when the ego vehicle changes lane to the fast lane for an overtake.

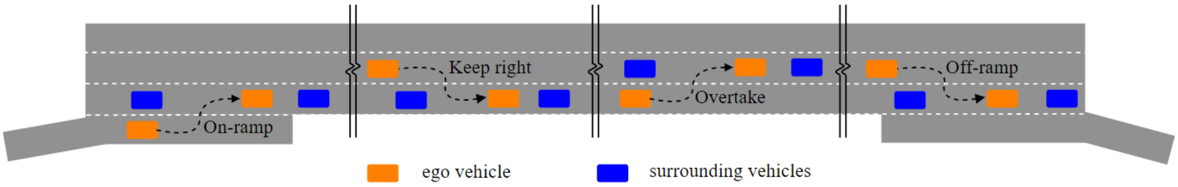


Figure 3-6 illustration of different lane change types.

It should be noted that, a limitation of 75m for the longitudinal distance for lane change gaps were considered for inclusion in the analysis. This is suggested by Yang et al. to determine that the ego vehicle has interaction with the lead vehicle (Yang et al., 2019). We considered this limitation for both lead and lag gaps. This way total merging gaps will be limited to maximum150m or around 6 seconds.

3.2.8 Analysis approach

A two-step analysis approach was implemented to test the research expectations. First, a principal component analysis was conducted on the answers to the MDSI questionnaire. The purpose was to determine the latent behavioural components relevant to the driving styles. Secondly, Linear Mixed Effects Models (LMM) were estimated to investigate the importance of several predictors (i.e. scenario, demographics, and driving style) on car following and lane changing behaviour of drivers. The analysis of the questionnaires and LMMs were performed using the Statistical Package for the Social Sciences (SPSS) version 25.0 and Python package *statsmodels* respectively (Seabold and Perktold, 2010).

3.3 Results

This section presents the results of the collected data in the experiment. The results of the questionnaire data is presented in Section 3.3.1. The descriptive statistics of the driving behaviour is presented in Section 3.3.2, followed by the results of the Linear Mixed Effects Models considering the three scenarios presented in Section 3.3.3.

3.3.1 Questionnaires

Multidimensional driving style inventory questionnaire (MDSI): A Principal Component Analysis (PCA) was conducted on the questions of MDSI questionnaire to combine variables which have a common background into a new variable (component). The PCA was performed with orthogonal rotation (varimax) and based on eigenvalues greater than 1. Since the number of participants who completed both the questionnaire and the simulator drives was considered low (51 participants) for PCA analysis, we conducted the PCA on the answers from all 182 respondents of the questionnaire. After checking communalities between indicators, four components were obtained, which cumulatively accounted for 47.94% of the total variance. Items with a communality lower than 0.4 were excluded from the exploratory factor analysis. The Kaiser-Meyer-Olkin measure of sampling adequacy was satisfactory (0.87) and Bartlett's test of sphericity was significant ($p < 0.0001$) which means that the data was suitable for the proposed statistical procedure of PCA (Williams et al., 2010). In conclusion, 35 out of the 44 questions were part of the final 4-component solution. The components are in line with the factors defined by Taubman-Ben-Ari et al. (2004). The latent variable Component 1 can best be described as "Risky" drivers, Component 2 reflects the driving style "Angry & high-velocity", Component 3 refers to "Dissociative & anxious" driving style, and finally, Component 4 refers to ‘‘Patient & careful" drivers. Figure 3-7 illustrates the distributions of each driving style for the 51 participants who completed the questionnaire and the experiment. As it can be seen in Figure 3-7, participants who completed the experiment mostly reported their driving styles as not "Risky" and not "Angry & high-velocity". However, their "Dissociative & anxious" driving style ranged from not "Dissociative & anxious" to very "Dissociative & anxious". Also, there were both not "Patient & careful" and very "Patient & careful" drivers.

Simulation Sickness Questionnaire: The mean score and the standard deviation of the simulation sickness questionnaire were also calculated. The score of SSQ reflects the symptomatology of participants' experience in the virtual environment. Higher scores mean higher symptoms. The maximum total score of the SSQ is 236 (Kennedy et al., 2003). The total score of all participants in this study was fairly low with a mean and standard deviation of 29.55 and 22.67, respectively which means the simulator study did not lead to serious simulation sickness.

Presence Questionnaire: Besides that, the score of the Presence Questionnaire was obtained. Summing the 19 responses of the core questions, the range of scores could be between 19 to 133. The total score of the PQ with a mean of 83.1 and a standard deviation of 12.44 indicated that participants experienced a higher-than-average amount of presence during the drive in the driving simulator.

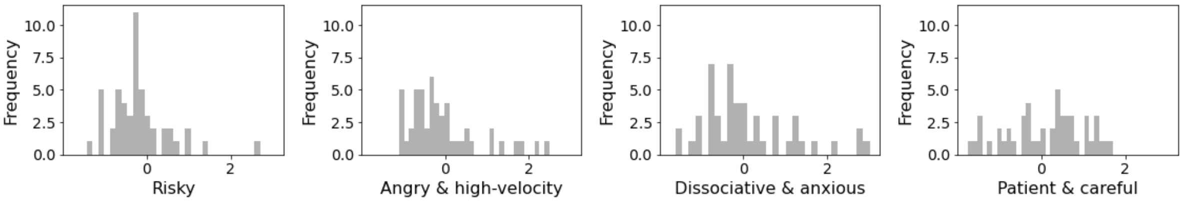


Figure 3-7 Driving styles distributions.

3.3.2 Driving behaviour descriptive statistics

Prior to conducting the analysis, the number of observations for each manoeuvre was derived for comparisons between scenarios. Based on the size of THW, longitudinal manoeuvres were divided into three different groups: a) free flow when the THW is larger than 3s and the speed of the ego vehicle is not restricted by any other vehicle, b) car-following when the THW is equal or smaller than 3s, and c) critical car-following when the THW is equal or smaller than 1.5s. The THW≤ 1.5s was chosen as the critical THW because in practice, the average THW during the capacity conditions of a Dutch freeways is approximately equal to 1.5s, which represents a capacity of 2.400 veh/hr/lane (Grontmij, 2015). As can be seen in Table 3-1, the number of observations for critical THW of the ego driver in DL scenario is considerably higher compared to Base and Mixed scenarios. The merge gaps are not equal across different scenarios, because: a) they are filtered by the 75m criterion (Yang et al., 2019), and b) some participants did not perform some of the merge manoeuvres. For example, they might have been driving on the slow lane and did not have to accept any off-ramp gaps, or they did not overtake or keep right as much as other drivers.

Table 3-1 number of observations for each manoeuvre per scenario

Car-following THWs	Number of observations			Merge gaps	Number of observations		
	Base	Mixed	DL		Base	Mixed	DL
Free flow THW	99081	134069	65114	On-ramp	111	80	109
Car-following THW	245747	195453	307666	Off-ramp	62	57	62
THW ≤ 1.5s	88350	64025	133167	Keep right	70	76	48
				Overtake	102	19	83

Boxplots of car following THWs were generated to see if there are any visible differences between scenarios and for each lane separately (Figure 3-8 (a, b, c)). The THWs on the fast lane were not shown since participants rarely entered that specific lane in Base and Mixed scenarios and were not allowed to drive on this lane in DL scenario. As it can be seen in the figure, car-following THWs of the ego vehicle are visibly smaller in DL scenario compared to the Mixed or Base scenarios, especially on the middle lane which is next to the dedicated lane where CAV platoons drive.

Three more boxplots were generated to examine the critical car following THWs, i.e., THW≤ 1.5s of ego drivers (Figure 3-8 (d, e, f)). The critical THWs in DL scenario and on the middle lane are obviously smaller compared to Base and Mixed scenarios (Figure 3-8 (f)). It shows that drivers are more likely to follow a car very closely when driving next to the DL where they were exposed to CAV platoons.

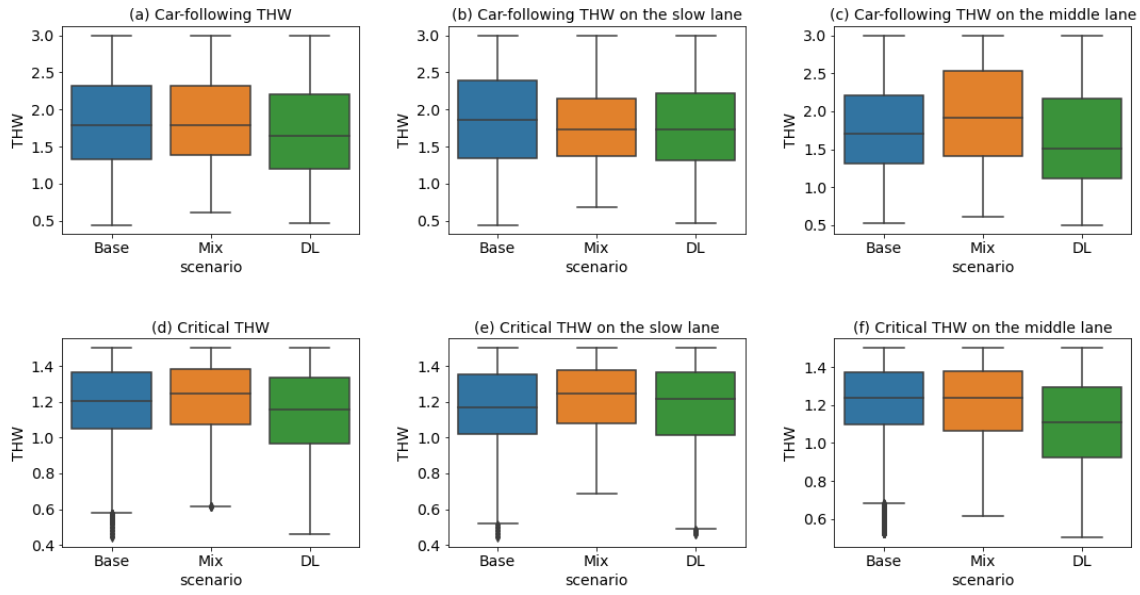


Figure 3-8 Boxplots of car-following THWs.

As far as the lane change gaps are concerned, the boxplots in Figure 3-9 shows that participants were more likely to accept smaller merging gaps in DL scenario.

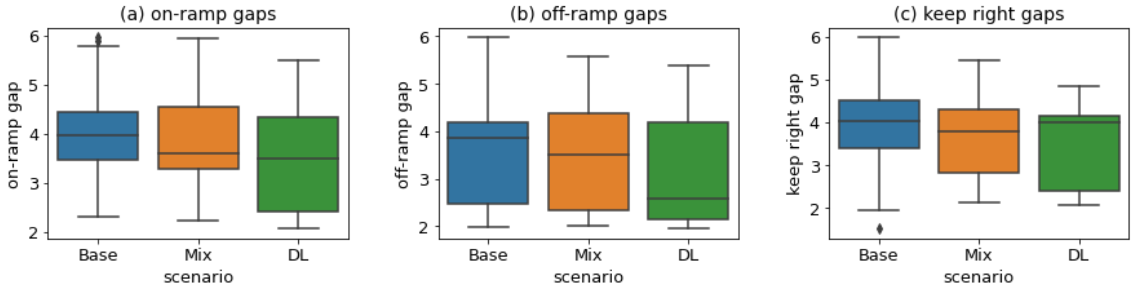


Figure 3-9 Boxplots of accepted merging gaps.

3.3.3 Linear Mixed Effects Models (LMM)

To find out whether or not the differences observed in the boxplots are statistically significant, Linear Mixed Effects Models (LMM) were conducted to compare the THWs and merging gaps across the different scenarios, taking into account the participants' demographics and driving styles derived from the MDSI questionnaire.

The LMM is a widely used method to analyse unbalanced longitudinal data, where individuals may be measured at different time points, or at even different number of time points. LMMs are able to consider random effects that cannot be controlled for in the experiment. Random effect models have been widely utilized for this purpose (Wang, Yang, & Hurwitz, 2019; Laird & Ware, 1982; Razmi Rad, Homem de Almeida Correia, & Hagenzieker, 2020).

We have fitted models with two random effects for each participant: a random intercept, and a random slope (with respect to scenario). The random intercept captures correlations between the observations from the same participant. This means that each participant may have a different baseline THW or merging gap due to their characteristics or driving styles. The random slope allows the explanatory variables to have a different effect for each participant. This means that each participant may change the THW or merging gap at a different rate. This is because different drivers may perceive and be influenced differently by the CAV platoons and the dedicated lane. So the rate of behavioural adaptation (if any) may be different for each participant.

In total, five LMMs (car-following THW, critical THW, on-ramp accepted gaps, off-ramp accepted gaps, and keep right accepted gaps) were developed, as shown in Table 3-2 to Table 3-4. Backward elimination method was used for the selection of variables. First the full independent variables were included in the model, then the most insignificant ones were eliminated until reaching a set of variables that all have a significant influence on the model.

3.3.3.1 Car-following behaviour

In order to compare the car-following behaviour in different scenarios, LMMs were developed considering the THWs equal or smaller than 3s. The LMMs were performed in two ways: Model (a) only considering the main independent variables without any interactions. Model (b) considering the main independent variables with possible interactions which appeared to be significant in the model.

As it is shown in Table 3-2, Model (a), in the DL scenario, the participants drove with significantly smaller THWs (0.128 s smaller), compared to the other two scenarios. The results also indicate that younger, male drivers kept smaller THWs in general compared to older female drivers. Finally, drivers with higher education kept larger THWs in general.

Considering Table 3-2, Model (b), although the THW is shown to be larger on the middle lane in general (0.012 s larger), when considering the interaction between the lane and scenario, the results reveal that THW is significantly smaller in DL scenario and on the middle lane when the participants drove right next to the CAV platoons on the dedicated lane (0.058 s smaller). It should be mentioned that the THWs on the fast lane were not included in LMM analysis since drivers rarely used this lane in Base and Mixed scenario and were not allowed to drive on it in DL scenario. Considering gender and education, we can see the same trend as explained in Model (a). Moreover, interesting results were found regarding age. Model (b) indicated that older drivers keep significantly larger THWs. However, when considering the interaction between age and scenario, it is found that older drivers decrease their car following THW in DL scenario compared to Base (significant at the 10% level), while this has not happened in Mixed scenario. It can be concluded that, older drivers are more likely to adapt their behaviour when driving next to platoons compared to young people.

Next, LMMs were developed for critical car-following behaviour considering THWs equal or smaller than 1.5 s. Table 3-3, Model (c) and Model (d) show the results of LMM without and with interactions, respectively. Similar to Model (a) shown in Table 3-2, Model (c) reveals that drivers drive significantly closer to their leaders in DL scenario compared to Base (0.042 s smaller). However, the coefficient indicates that this decrease in critical THW is not as high as the decrease in car-following THW (0.128 s) in Model (a).

Table 3-2 Linear Mixed Effects Model for car-following (THW ≤ 3 s).

		Model (a)			Model (b)		
		Coefficient	**p-value**	**Z**	**Coefficient**	**p-value**	**Z**
Intercept		1.337	<0.001	7.047	1.304	<0.001	6.805
Scenario	DL (vs. Base)	-0.128	0.029	-2.187	0.025	0.783	0.275
	Mix (vs. Base)	0.023	0.693	0.395	-0.036	0.698	-0.388
Gender	Female (vs. Male)	0.158	0.061	1.871	0.157	0.062	1.866
Lane	Middle (vs. Slow)	0.056	<0.001	37.776	0.012	<0.001	5.217
Age		0.048	0.003	3.015	0.060	0.001	3.356
Education		0.086	0.033	2.130	0.088	0.029	2.180
Lane * Scenario	Middle (vs. Slow), DL (vs. Base)				-0.058	<0.001	-17.141
	Middle (vs. Slow), Mixed (vs. Base)				0.249	<0.001	66.543
Age * Scenario	Middle (vs. Slow), DL (vs. Base)				-0.033	0.084	-1.730
	Middle (vs. Slow), Mixed (vs. Base)				-0.013	0.527	-0.632
Statistics							
Number of observations		748866			748866		
Number of groups		51			51		
Log-likelihood		-536450.24			-532901.1		
AIC		1072912.48			1065818.2		
BIC		1072981.64			1065910.41		

Table 3-3 Linear Mixed Effects Model for critical car-following (THW≤ 1.5s)

		Model (c)			Model (d)		
		Coefficient	**p-value**	**Z**	**Coefficient**	**p-value**	**Z**
Intercept		1.029	<0.001	17.284	1.020	<0.001	17.038
Scenario	DL (vs. Base)	-0.042	0.038	-2.072	-0.023	0.251	-1.148
	Mixed (vs. Base)	0.021	0.340	0.954	0.026	0.249	1.153
Age		0.016	0.003	2.979	0.017	0.003	3.013
Education		0.044	0.001	3.291	0.044	0.001	3.259
Lane	Middle (vs. Slow)	0.001	0.155	1.422	0.023	<0.001	15.319
Lane * Scenario	Middle (vs. Slow), DL (vs. Base)				-0.046	<0.001	-22.875
	Middle (vs. Slow), Mixed (vs. Base)				-0.011	<0.001	-4.625
Statistics							
Number of observations		285542			285542		
Number of groups		51			51		
Log-likelihood		110241.43			110523.29		
AIC		-220472.86			-221034.58		
BIC		-220420.05			-220971.21		

In line with the results of the car-following behaviour in Table 3-2, older drivers and drivers with high education increased their critical THW relative to their leaders. Considering Model (d) including the interactions, it can be seen that drivers decreased their critical THWs on the middle lane in both DL and Mixed scenario. However, the decrease in DL scenario is more than four times larger than in Mixed scenario (0.046 s and 0.011 s decrease in DL and Mixed respectively).

3.3.3.2 Lane change behaviour

Three LMMs were also performed to compare the lane change accepted gaps between the different scenarios. Table 3-4 illustrates that off-ramp and on-ramp accepted gaps were significantly shorter in DL compared to Base scenario.

In terms of keep right lane changes, scenario turned out to be a significant factor once again. Table 3-4 indicates that keep right gaps were decreased in Mixed and DL scenario compared to Base. However, the coefficient shows that this decrease is greater in DL compared to Mixed scenario.

Lane changes which were performed in order to overtake were also studied. No specific trend was found in these type of lane changes.

It should also be mentioned that driving styles derived from MDSI were not statistically significant in any of the LMM models.

Table 3-4 Linear Mixed Effects Models for off-ramp, on-ramp, and keep right accepted gaps

		Off-ramp			On-ramp			Keep right		
		Coef.	**p-value**	**Z**	**Coef.**	**p-value**	**Z**	**Coef.**	**p-value**	**Z**
Intercept		3.524	<0.001	28.941	4.019	<0.001	39.469	3.961	<0.001	29.437
Scenario	DL (vs. Base)	-0.383	0.026	-2.230	-0.578	<0.001	-4.068	-0.431	0.028	-2.199
	Mix (vs. Base)	-0.035	0.852	-0.187	-0.154	0.298	-1.042	-0.361	0.026	-2.223
Statistics										
Number of observations				181			300			194
Number of groups				45			51			45
Log-likelihood				-254.28			-416.77			-263.00
AIC				512.56			837.54			530
BIC				518.96			844.95			536.54

3.4 Discussion

In this section, the results are summarized and discussed according to the expectations proposed in the introduction.

3.4.1 Behavioural adaptation in Mixed situation

The first expectation was that behavioural adaptation would be negligible in a mixed traffic of CAVs and MVs at moderate MPRs. One of the scenarios in the experiment was to drive on a freeway with mixed traffic of MVs and CAVs while the MPR of CAVs was 43% (Mixed scenario). The objective was to compare the car-following and critical THWs (THW $\leq$ 3 s and THW $\leq$ 1.5 s respectively) and lane change gaps in mixed scenario with Base when there were no CAVs around (representative of the current situation) with the same traffic flow per lane as the Mixed scenario. LMM compared the THWs in both situations and revealed that there is no significant difference in car-following THWs between the two scenarios. This shows that the few number of platoons which were scarce on the freeway did not influence the car-following behaviour of MV drivers. Regarding the lane change gaps, the comparison of Base and Mixed scenario showed that no significant changes happened in on-ramp and off-ramp gaps when driving next to few platoons for a short time.

In fact the exposure time (the time when the ego vehicle was driving next to a platoon) was too short to influence the behaviour of MV drivers (Gouy et al., 2014). Moreover, in the current experiment the number of platoons and the platoon size were kept very low to represent the MPR of 43%. So, the conspicuity of the platoons was not high enough to influence the car-following and lane changing behaviour of MV drivers. This confirms the conclusions obtained by Gouy et al. which indicated that exposure time and conspicuity of platoons are important factors in behavioural adaptation of MV drivers (Gouy et al., 2014). They also indicated that there was no carry over effect in behavioural adaptation from the situation when car-following happened next to platoons keeping short THW (0.3 s) to long THW (1.4 s). This supports the fact that driving next to a platoon for a few seconds cannot influence the car-following behaviour for the entire drive.

On the other hand, considering the keep right manoeuvres, LMM revealed that merging gaps decreased significantly in Mixed scenario compared to Base. Keep right gaps were not significantly different between DL and Mixed scenario. However, because Base was always the first scenario to drive, the participants might have gotten used to the simulator environment and feel more comfortable to accept shorter gaps when they drove in Mixed and DL scenarios.

3.4.2 Behavioural adaptation when driving next to dedicated lanes:

The second expectation stated that with concentrating CAV platoons on one lane (the DL), the car-following THWs (Expectation 2a) and lane change gaps (Expectation 2b) will decrease significantly due to behavioural adaptation. To test this expectation, participants were asked to drive on a freeway with one dedicated lane to CAV platoons. The comparison between Base and DL scenario showed that MV drivers significantly decreased their car-following THW and critical THW in DL scenario, especially when they were driving on the lane adjacent to DL where platoons drive. In fact, when platoons were concentrated on one lane, their exposure time and conspicuity was increased to the extent that it influenced the car-following behaviour of MV drivers. This is in line with the results of previous experiment when participants were asked to drive next to continuous access DL and limited access DL with buffer (Schoenmakers et al., 2021). This also confirms the other two experiments of Gouy et al. with no dedicated lane (Gouy et al., 2013; Gouy et al., 2014). Although there was no dedicated lane proposed in those experiments, the fast lane of the freeway was in practice used as a dedicated lane since all CAVs were driving on that lane.

It has been concluded from a previous study that MV drivers tend to show more “radical behaviour” by greater steering magnitude and steering velocity when they change lanes into a CAV lane (Lee et al., 2018). Similarly, in this study, it appeared that MV drivers accept shorter gaps when changing lane for on-ramps, off-ramps and keep right manoeuvres (Expectation 2b confirmed). Given that the traffic flows were equal per lane for all scenarios, accepting smaller gaps could be a result of imitating the behaviour of CAVs and is unlikely to be affected by the offered gaps in traffic.

3.4.3 Behavioural adaptation and the impacts of demographics and driving style

Expectation 3 indicated that participants’ demographics and driving styles play important roles in behavioural adaptation in car-following and lane changing. The results of LMM for car-following THW showed that male drivers follow their leaders keeping smaller THWs. This is in line with the results from the literature which revealed a positive correlation between being a male driver and close car-following and shorter gap-acceptance in lane changing (Rajalin et al., 1997; Farah, 2011). However, gender impact was not seen in critical THWs.

Furthermore, driver education turned out to be a significant predictor in car-following behaviour. Drivers with high education followed their leaders with larger THWs in all scenarios and did not adapt their car-following behaviour in DL scenario even when they drove on the lane adjacent to CAV platoons. This can be explained by the fact that people with higher education usually are more aware of the new technologies and may be more familiar with CAV behaviour and can distinguish the difference between CAVs and own capabilities in relation to close car-following. Moreover, some of the participants with higher education who participated in the experiment were students of the same department who worked directly in the fields related to CAVs.

Finally, younger drivers kept smaller THWs in car-following. This is in line with the findings of Rajalin et al. which showed that younger drivers tend to follow their leader more closely (Rajalin et al., 1997). Moreover, examining the interaction between age and scenario revealed that older drivers adapt their behaviour more than younger ones when driving on a highway with a dedicated lane to CAV platoons. This was shown by a significant decrease in car-following THW in DL scenario compared to the other two scenarios. However, this decrease was not seen in critical THW which shows that unwanted behavioural adaptation may occur to older drivers in car-following but not to the extend which leads to risky behaviour (at least at moderate MPRs of CAVs). Thus research on the impacts of age on behavioural adaptation is recommended to further support these results.

Furthermore, driving style did not influence the behavioural adaptation of MV drivers in car-following and lane changing. Similar findings can be seen in the study of Hoedemaeker & Brookhuis (1998) which revealed that driving style made little difference to the behavioural adaptation of drivers. This may indicate that other factors like the infrastructure, exposure time, and conspicuity of the CAV platoons in addition to driving style, determine the behaviour of drivers in car-following and lane changing.

3.5 Conclusions and future work

This study investigated the behavioural adaptation of drivers of MVs in car-following and lane changing when driving in a mixed traffic with CAV platoons as well as driving on separate lanes but adjacent to the CAV dedicated lane at a moderate MPR (43%). Based on the results, MV drivers are not likely to adapt their behaviour in car-following and lane changing in mixed traffic situation at moderate MPR of CAVs. However, at the same MPR, implementing a DL would increase the density of CAVs on one lane and consequently increases the exposure time and conspicuity of CAV platoons. So, MV drivers could see the CAV platoons keeping very short THWs more often. This leads to a situation where MV drivers tend to imitate the behaviour of CAV platoons by following a lead car more closely and accepting shorter gaps in lane changing.

Behavioural adaptation is not necessarily considered negative as long as it is not leading to risky manoeuvres which a human driver is not able to control. In fact, adopting shorter THWs (in manageable range by a human) in car-following could increase the capacity of a freeway. So, if MVs are equipped with systems such as collision avoidance to avoid close car-following by the time we accommodate CAV platoons on our road network, risky manoeuvres can be avoided. However, it requires time and budget to replace the entire vehicle fleet with new ones. This way we can avoid the potential unsafe consequences of behavioural adaptation and exploit the smoothness of the traffic flow generated by CAVs.

This study further gave insights regarding the impacts of demographics and driving styles of MV drivers on their behavioural adaptation. Age, gender, and education turned out to be significant factors in car-following as expected based on literature. More interestingly, it was observed that older drivers are more prone to behavioural adaptation in car-following but not to the extend which leads to critical or risky behaviour. Moreover, drivers with higher education showed no behavioural adaptation when driving next to CAV platoons. This could be because of their higher information regarding CAV technology. Therefore, it would also be important to investigate whether human drivers still imitate the behaviour of CAVs after they are educated about the differences between human driver and CAV capabilities.

Due to both technical and ethical reasons, it was not possible to perform a field test, therefore, a virtual reality environment was used to investigate the study research question. This brings along questions regarding real-world behavioural adaptation of MV drivers. Therefore, future pilot field tests would be needed to validate the results. Moreover, behavioural adaptation was measured over a limited time and at only one MPR (43%). Thus, future research is needed on the long-term effects of behavioural adaptation and at different MPRs.

Chapter 4

The Impact of the Presence and Utilization Policy of a Dedicated Lane on Drivers′ Preference to Use Automation and Driving Behaviour on Motorways

Results in Chapter 3 showed that the presence of a DL can influence the driving behaviour of drivers of manual vehicles. It is also relevant, based on the research agenda in Chapter 2, to investigate the impacts of the presence of such a lane on the behaviour of drivers of CAVs.

To accomplish this, a driving simulator experiment is conducted in this chapter, where participants drive a CAV in the presence of a DL with different utilization policies while having the possibility to choose between driving in an automated mode and resuming manual control. In automated mode the participants could adjust the driving speed and time headway and initiate automated lane change. The impact of presence and utilization policy of the DL on drivers' preference to use automation and their behaviour in car-following and lane changing is investigated in this chapter.

This chapter is currently under review for journal publication. **Razmi Rad, S.**, Farah, H., Taale, H., van Arem, B., Hoogendoorn, S.P. (under review). The Impact of the Presence and Utilization Policy of a Dedicated Lane on Drivers' Preference to Use Automation and Driving Behaviour on Motorways

4.1 Introduction

The introduction of Connected and Automated Vehicles (CAVs) into the transportation system is expected to increase the capacity of the road network, especially if platooning is involved (Harwood and Reed, 2014). Simulation studies have reported an increase in motorway capacity as the penetration rate of CAVs increases assuming that these vehicles are able to drive in platoons keeping smaller than normal THWs in the range of 0.3 to 1.1 seconds (Vander Laan and Sadabadi, 2017; Liu et al., 2018a). However, mass adoption of small THWs as assumed for platooning in these studies depends on the user's acceptance, trust, and preferences (Sarker et al., 2020). Moreover, dedicating a lane to CAVs at moderate market penetration rates can further increase the capacity and the efficiency of the motorway by facilitating platooning of CAVs (Van Arem et al., 2006; Chen, 2021; Zhong et al., 2021; Hamad and Alozi, 2022). Although simulation studies have shown that a dedicated lane (DL) can improve the efficiency of the motorways (Madadi et al., 2021; Kumar et al., 2020), behavioural studies on the impacts of the presence and utilization policy of such a lane on the behaviour of CAV drivers is largely lacking in the literature.

According to Horswill and McKenna (1999), people tend to take lower risks and possibly choose larger THWs when they are not in control of driving. Another example is a study by Basu et al. (2017) which revealed that drivers prefer a significantly more defensive driving style in an automated vehicle compared to their own driving style. In their study, the participants were asked to drive in manual and fully automated modes in a driving simulator on two different days. A significant difference was found between how the users drive and how they prefer to be driven by the automated vehicle, which is in a more defensive driving style. In fact, the participants wanted the automated vehicle to drive like they *think* they drive but not like how they drive. Therefore, the relation between automated driving and THW is not as simple as it seems.

Regarding THW preference, Nowakowski et al. (2011) conducted a field study to assess drivers' choices of following distances in automated driving. Sixteen drivers were asked to drive vehicles equipped with ACC, cooperative ACC (CACC), or no driver assistance features, for a total duration of 13 days. According to the results, the shortest THW settings available by the ACC and CACC equipped vehicles were chosen most frequently by the participating drivers. The mean for manual car-following THW was 1.64 s, while the means for the selected THWs for the ACC and CACC equipped vehicles were approximately 1.54 s and 0.72 s, respectively. Thus, drivers were willing to select smaller THWs in ACC and CACC settings. However, it is worth pointing out that the actual THW during the drives could be smaller or larger.

On the contrary, Kessler et al. (2012) reported a 16% increase in the size of THW when using ACC in a field test. The authors asked participants to drive a vehicle equipped with ACC and forward collision warning for a duration of 12 months. As a result, and contrary to Nowakowski et al. (2011), participants drove with larger THWs with ACC. They also chose higher speeds in ACC mode. However, the researchers suggested that higher speeds could be due to drivers' choice of when to use ACC (i.e., high speed motorways). Similarly, another driving simulator study by Bianchi Piccinini et al. (2014) resulted in larger THW adoption when using ACC. But, contrary to Kessler et al. (2012), participants, on average, drove with lower speeds. Those who had ACC experience, however, drove faster and closer to the lead vehicle.

Schakel et al. (2017) conducted a naturalistic driving study with 8 participants to compare driving behaviour with ACC on and off. The subjects drove their own ACC-equipped vehicle on freeways for a duration of 4 to 5 weeks. In total, 48 hours of driving data were recorded. In line with Kessler et al. (2012) and Bianchi Piccinini et al. (2014), the average THW was larger with ACC on. The increase in THW while using ACC in the aforementioned studies, could be due to the predefined settings of the system which prevented intended or unintended small THWs. While in CACC mode, the system allowed very close car-following (small THWs) in platoons.

Results of these studies imply that human drivers behave differently when driving in automated mode compared to when they driver in manual mode. In this regard, a question that may arise is the following: “how would be the behaviour of drivers in terms of car-following and gap acceptance in lane changing when driving on a dedicated lane (DL) knowing all vehicles are automated?”. Human drivers behave differently when interacting with automated vehicles compared to manual ones. For example, they accept significantly smaller critical gaps and maintain a significantly shorter THW when the approaching vehicle is demonstrably an automated one (Soni et al., 2022). Thus, given that all vehicles on a DL are automated, the behaviour of human drivers might be different on DLs.

Trust in and acceptance of automation technology could also have an impact on driver behaviour. Hjälmdahl et al. (2017) conducted an experiment to assess drivers’ trust and acceptance of automated truck platooning. The truck drivers performed three drives in a driving simulator with three conditions: a) standard Scania cruise control with constant speed of 82 km/h as the baseline condition, b) a longitudinal control with 10 metres distance gap to the truck in front, and c) autonomous longitudinal and lateral control as a CAV. The researchers used the questionnaire developed by Jian et al. (2000) to measure trust in automation based on subjects’ experience of automation during the experiment. Additionally, user acceptance was assessed using Acceptance Scale for Advanced Transport Telematics by Van Der Laan et al. (1997) and Questionnaire for User Interface Satisfaction by Chin et al. (1987). According to the results, acceptance and trust scores were in general higher in baseline drive than with longitudinal or full automation. More recently, a driving simulator study investigated the factors that may influence drivers’ willingness to engage in automation during every day driving (Tomasevic et al., 2022). It was found that drivers were less willing to engage automation in car following situations compared to free-flow driving. They defined following situation as car-following events with THWs less than 1.5s while free-flow driving was driving with a desired choice of lane and velocity, and comfortable THW as defined by Fastenmeier and Gstalter (2007).

Another relevant question is: “to what extent a DL can influence CAV drivers’ preference to use automation given all interacting vehicles on their driving lane are automated?” Different utilization policies, such as mandatory versus optional use of a DL by CAVs, could have an impact on traffic performance and traffic safety (Talebpour et al., 2017; He et al., 2022). Driving simulator and field studies are needed to shed light on the impacts of a DL for CAVs on the car-following and lane changing behaviour of a CAV driver under different utilization policies (Razmi Rad et al., 2020a).

In addition, other driver characteristics play a role in driving behaviour and preference to use automation. The literature suggests that age, gender, and education level of drivers can be predictors of preferences to use automation or driving behaviour (Rödel et al., 2014; Piao et al., 2005; Kadylak et al., 2021; Nielsen and Haustein, 2018). Thus, it is relevant to study the behaviour of different groups of drivers in relation to preferences to use automation and driving behaviour in different modes and on different lane types.

The main objective of this study is to investigate the impact of presence and utilization policy of a DL on drivers’ preference to use automation in car-following and lane changing, taking into account the relevant human factors. Moreover, this study aims to study the behaviour of CAV drivers in car-following and lane changing in different driving modes (i.e., automated vs. manual) and on different lane types (i.e., normal vs. dedicated lanes). It should be noted that, in this paper, CAV refers to connected and automated vehicles which are able to drive in platoons keeping short THWs (0.3 s), which corresponds to SAE levels 4 and 5 (SAE, 2018).

Due to technical and ethical issues, a driving simulator experiment was the most suitable method to address the aim of this study. Participants in the experiment were asked to perform car-following and lane changing in both automated and manual mode in different scenarios with and without dedicated lanes with different utilization policies.

In the remainder of the article, the methodology is described in section 4.2 and the results of the driving simulator experiment are presented in section 4.3. Finally, the main findings are discussed in section 4.4 and the conclusions are drawn, leading to recommendations for further research in section 4.5.

4.2 Methodology

The following sub-sections explain the apparatus set-up, the driving simulator scenarios, the experimental procedure, questionnaires used, data collection and processing, the recruitment of participants for the driving simulator experiment, and finally the analysis approach.

4.2.1 Apparatus

The study was conducted in a fixed-based driving simulator comprised of a dashboard mock-up with three 4K high resolution screens, providing approximately a 180° vision, Fanatec steering wheel, pedals, and a blinker control. The participants could switch between automated and manual mode via buttons on the steering wheel. The automated mode included functionalities such as speed and time headway control as well as automated lane change. The participants could adjust their car following time headway using the right most buttons on the steering wheel shown in Figure 4-1. Three different time headways were available to choose from: 0.5s, 1s, and 1.5s. The time headway of 1s was chosen as the default in each run. As soon as a participant changed the time headway, the system remembered this and would begin the next automated drive with the specified time headway. They could also see the adjusted time headway icon on the screen as shown in Figure 4-2. Since the term *'time headway'* is not familiar to most participants, we used *'distance to the lead vehicle'* in the instructions for the participants and used the letter 'D' on the buttons with an upward arrow for increasing the headway, and downward arrow for decreasing the headway. It should be noted that the lane change behaviour in automation was also dependant on the car-following.

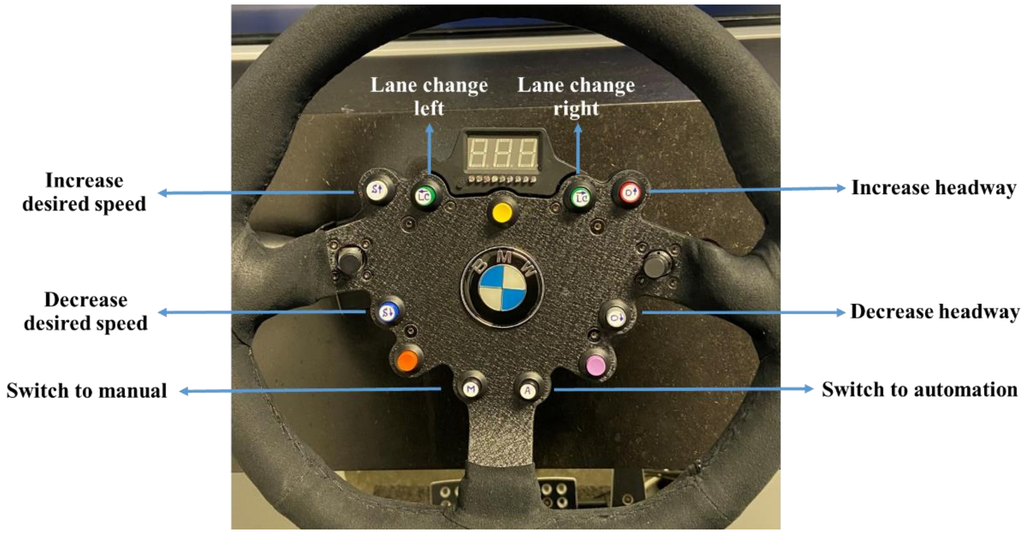


Figure 4-1 The steering wheel including the different buttons to adjust the automated driving mode.

Two more buttons (left side of the steering wheel) were assigned to increase and decrease the desired driving speed by participants as shown in Figure 4-1. One short button press would change the speed by 5 km/h. As soon as the desired speed was set by the participants, a text massage would appear on the screen stating, for example: ***"The desired speed is 70km/h"***. Lane changes were also possible in automated mode using the buttons on the upper most part of the steering wheel to change lane to the right or left.

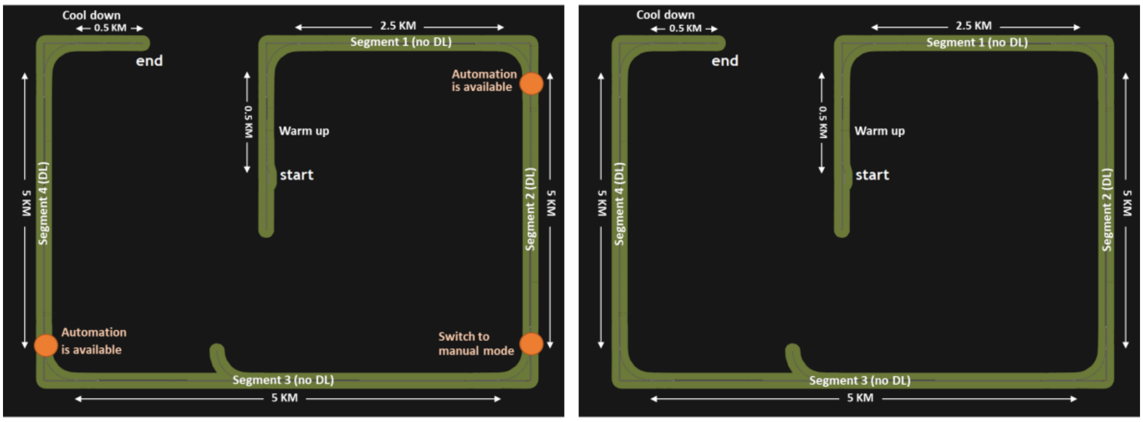
When automation was active, the throttle, the brake pedals and the steering wheel were inactive, while in manual mode, all the automation functionalities were inactive. Participants could also see on the screen in which mode they were driving. In automated mode, they could constantly see the adjusted time headway and speed on the screen. While in manual mode, they could see a notification on the screen stating: ***"you are driving manually".***

(a) (b) (c)

Figure 4-2 Time headway icons appearing on the screen, (a) 0.5s, (b) 1s, and (c) 1.5s.

4.2.2 Design of the driving environment

The simulated road environment consisted of a typical three-lane Dutch motorway containing six road segments, connected to each other with on- and off-ramps via large curves as illustrated in Figure 4-3. The starting and finishing segments were designed as warm up and cool down segments respectively and were excluded from the analysis. In segments 1 and 3 of the motorway, no DL was present while in segments 2 and 4 the median lane was dedicated to CAVs. Two scenarios were developed which had different driving instructions.



(a) (b)

Figure 4-3 top view of the road network, (a) *Mandatory* scenario; (b) *Optional* scenario.

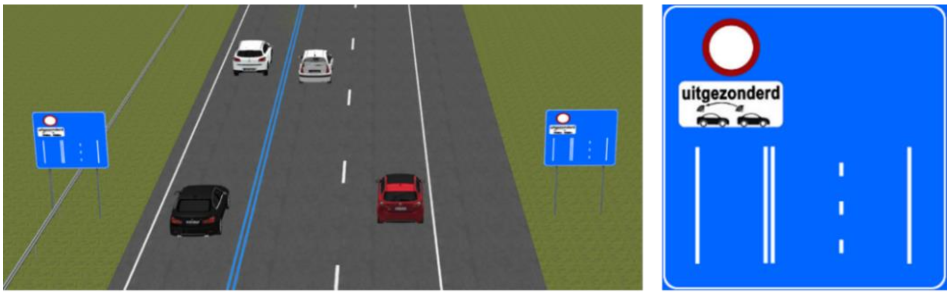
Mandatory dedicated lane (Figure 4-3 (a)): In the two sections of the motorway where a DL was present, the left most lane (median lane) of the motorway was dedicated to CAVs and therefore, CAVs had to drive on the DL when in automated mode and were not allowed to drive on the normal lanes (NLs) unless the driver switched to manual mode. The participants were told to switch to automated mode before changing lane towards a DL. Platoons of 2 to 3 vehicles drove on the DL and the PR was 40%. Intra-platoon and inter-platoon THWs were set to ranges of “0.5s -1s” and “2s - 4s”, respectively. To inform the participants about the dedicated lane and to further clarify the purpose of this lane, a buffer demarcation separating the DL and the other lanes was applied together with road signs with a platooning pictogram, following Razmi Rad et al. (2021), as illustrated in Figure 4-4(b).

During *Mandatory* scenario, just before the beginning of segment 3 without a DL (see Figure 4-3(a)), the participants were notified, via a text message appearing on the screen stating ***“Please switch to manual mode”***, to switch to manual mode and continue driving manually. When automation was available at the beginning of segments 2 and 4 with DL, the participants were notified, via a text massage ***“automation is available”***, stating that automation was available and they had the freedom to decide to switch to automated mode and thus to the DL, or continue driving manually on the NLs.

Optional dedicated lane (Figure 4-3 (b)): In this scenario everything was designed the same as *Mandatory* scenario except that no notification was presented on the screen, and the use of the DL was optional, meaning that all lanes could be used by CAVs, while manual driving was not allowed on the DLs. Like the *Mandatory* scenario, drivers had the freedom to switch to automated mode (also on the NLs) or continue driving manually.

It should be noted that, switching to automation was not mandatory in any of the scenarios. In other words, the participants could choose to drive in manual mode and stay on the normal lanes or switch to automated mode and change lane to the DL in the *Mandatory* scenario or drive automated on any of the lanes in *Optional* scenario. This means that in *Mandatory* scenario and no DL (segments 1 and 3), drivers had to drive manually.

Each scenario was completed in a separate drive. Therefore, each participant drove the network twice, in *Mandatory* scenario and in *Optional* scenario. This is because the participants needed to be notified about the utilization policy of the DL before starting each drive, according to *Mandatory* or *Optional* scenario as explained above. The order of the drives was randomized between the participants. Each drive started with a manual drive on a section without a DL.



(a) (b)

Figure 4-4 (a) DL demarcation, (b) Road sign for DL (“uitgezonderd” means “except for” in Dutch).

4.2.3 Experimental design and procedure

The experiment consisted of two consecutive drives in the driving simulator. Each drive started from a parking lot. The participants entered the motorway via an on-ramp and followed the road signs towards their destination ‘Delft’, as was given to them at the beginning of the experiment. The procedure of the experiment was explained in a leaflet that was presented to the participants before the drives. They were also advised to stop the experiment if they felt any discomfort (i.e., simulation sickness), or take a short break between the two drives if they needed to. The participants were asked prior to the start of the experiment to sign a consent form and give their agreement to use their data for the research. The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology. Some COVID-19 related measures were also taken, such as: physical distancing, improved ventilation, sanitizing the desk, laptop, and steering wheel, and a buffer of 15 minutes between sessions. Each participant was rewarded with a voucher of €15 for participating in the experiment.

4.2.4 Questionnaires

The participants were also asked to fill in a set of questionnaires. The first questionnaire was administered to the participants to obtain information about their demographics and level of familiarity, experience, and trust in vehicle automation. To assess familiarity, the participants were asked the question: “How familiar are you with the concept of automated vehicles?” with possible answers: 1) I have never heard of automated vehicles; 2) I have heard about automated vehicles once or twice; 3) I am fairly familiar with the idea of automated vehicles; 4) I follow the developments of automated vehicles; and 5) I work in a field directly related to automated vehicles. They were also asked if they have any driver assistant features (e.g., cruise control, adaptive cruise control, lane keeping system, and automated lane change) in their vehicle and how often they use these functions.

The questionnaire developed by Jian et al. (2000) was used for measuring participants’ level of trust according to their experience during the experiment drives. It contained twelve statements for evaluating trust in automation and could be rated on a 7-point Likert scale from 1 (Not at all) to 7 (Extremely). The participants rated the twelve statements for car-following and lane changing separately.

The Simulation Sickness Questionnaire by Kennedy et al. (1993) was used after the experiment to measure if participants experienced any discomfort such as nausea, oculomotor discomfort, and disorientation, throughout the experiment while driving. Participants reported how much they felt affected by each symptom on a 4-point Likert scale from 0 (no) to 3 (severe).

Finally the 19 core items of the Presence Questionnaire (Witmer et al., 2005) examined participants’ presence during the drives. Four factors were considered, namely involvement, visual fidelity, adaptation/immersion, and interface quality which influence user presence during the drives with the driving simulator. The items were rated on a 7-point Likert scale from 1 (Not at all) to 7 (Extremely).

4.2.5 Data collection and processing

During the experiment runs, the driving simulator registered every 0.5 second the following variables for the ego vehicle and its surrounding agents: speed [m/s], position (x, y, z), headings (direction of movement), driving lane (i.e., slow, middle, and median), car following and lane changing mode (automated or manual).

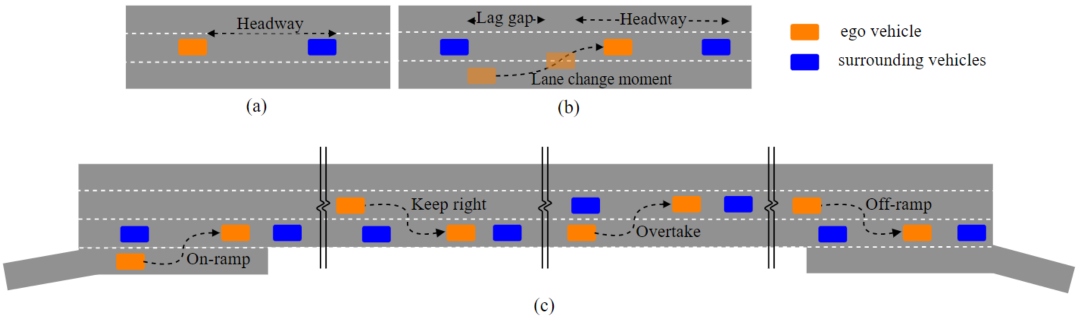


Figure 4-5 (a) Headway during car-following and (b) lead and lag gaps during lane changing, (c) different types of lane changes.

Based on the vehicle trajectory raw data, the following driving behaviour characteristics were calculated:

- **Time headway (THW) in car-following** was calculated as the distance between ego and lead vehicle plus the length of the lead vehicle (headway) [m] divided by the speed of the ego vehicle [m/s] (see Figure 4-5(a)). The THW was recorded from five seconds after a lane change till five seconds before the next lane change. This is to exclude those moments just before or after a lane change when the driver adjusts the gap to the car following situation (Razmi Rad et al., 2021). In addition, to exclude free flow driving, car-following was defined as situations when the ego vehicle is following a lead vehicle with THW equal or less than 3s (Pasanen & Salmivaara, 1993; Highway Capacity Manual, 2010).
- **Lane changing gap** was calculated as the sum of the headway [m] divided by the speed of the ego vehicle and distance between ego and lag vehicles (lag gap) [m] divided by the speed of the lag vehicle [m/s]. A lane change moment is when the front centre of the ego vehicle passes the lane marking (see Figure 4-5 (b)). Four types of lane changes were defined as illustrated in Figure 4-5 (c):
- **On-ramp**: when the ego vehicle accepts a gap to enter and merge into the motorway from an on-ramp (acceleration lane).
- **Off-ramp**: when the ego vehicle accepts a gap to change lane from the middle lane to the slow lane to exit the motorway via an off-ramp (deceleration lane). This type of lane change happened when the deceleration lane was available, and the participants have already seen the road sign showing their destination.
- **Keep right**: when the ego vehicle changes lane from the middle lane to the slow lane or from the median lane to the middle lane after completing an overtaking.
- **Overtake**: when the ego vehicle changes lane from the slow lane to the middle lane or from the middle lane to the median lane for overtaking.

According to Yang et al. (2019), during merging, the ego vehicle has interaction with a lead or a lag vehicle if the longitudinal distance is less than 75m. So, a limitation of 75m for the longitudinal distance for lane change gaps was considered for both lead and lag gaps.

4.2.6 Participants

A total of 48 participants (13 females, 35 males) took part in the experiment. They were recruited via a newspaper advertisement and an advertisement on the Delft University of Technology campus (Delft, The Netherlands). All participants held a valid driver's license and had a driving experience on Dutch motorways for at least three years. Their age and gender distribution is illustrated in Figure 4-6.

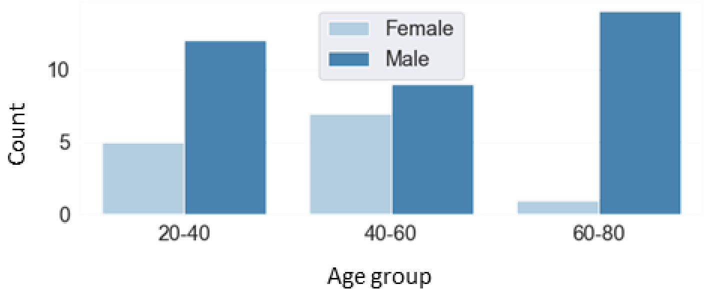


Figure 4-6 Age and gender distribution of the participants.

4.2.7 Analysis approach

Descriptive statistics of the questionnaires and the driving behaviour were first conducted. Next, drivers' preference to use automation in the two scenarios and based on the availability of a DL were investigated by plotting the observations. Additionally, to understand which variables can explain drivers' preference to use automation in car-following and lane changing, Linear Mixed Effects Models (LMM) were estimated for the automation use (Yes/No). Finally, LMMs were estimated to investigate the effects of scenario variables and driver characteristics on car-following and lane changing behaviour. Here the dependant variable is THW in car-following, or merge gap in lane changing. The analyses were performed using the Python package 'statsmodels' (Seabold and Perktold, 2010).

4.3 Results

The results of the questionnaire data, descriptive statistics, drivers' preference to use automation, and finally the driving behaviour in different modes and on different lane types are presented in this section.

4.3.1 Questionnaires

Table 4-1 presents the trust, simulation sickness and the presence questionnaires scores.

Trust questionnaire: The scores of this questionnaire report participants' level of trust according to their experience during the drives. Considering the 12 statements of the questionnaire, the trust score could range between 12 to 84. The average trust scores of all participants were 54.5 and 53.7 with standard deviations of 8.8 and 8.5 for car-following and lane changing, respectively. Therefore, the mean trust scores of all participants in both car-following and lane changing manoeuvres were moderately high.

Simulation Sickness Questionnaire (SSQ): The score of SSQ reflects the symptomatology of participants' experience during the drives in the driving simulator with the maximum total score of 236 (Kennedy et al., 2003). The simulator study did not lead to serious simulation sickness since the mean of the total score of all participants was fairly low (29.1).

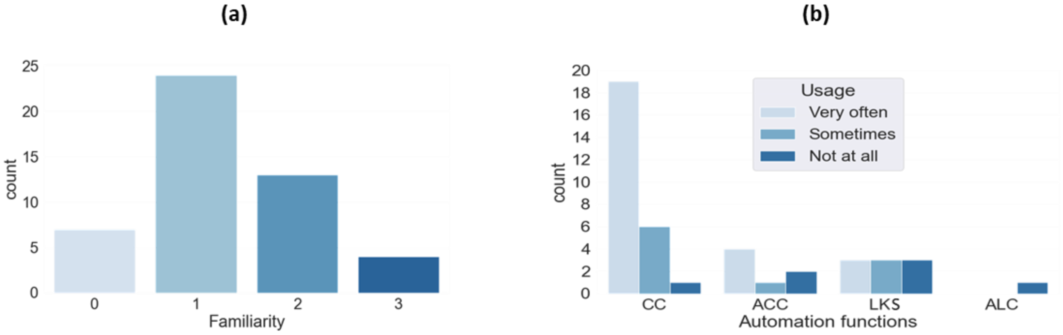
Presence Questionnaire (PQ): The PQ score could range between 19 to 133 summing the 19 responses of the core questions. Higher scores mean better presence of subjects during the experiment. The average presence score of all participants was 93 with a standard deviation of 14.8. Therefore, the mean of the PQ score has a higher-than-average amount of presence during the drive in the driving simulator.

Table 4-1 Scores of Trust, Simulation Sickness Questionnaire (SSQ), and Presence Questionnaire (PQ)

	mean	Std.	min	max	Range
Trust in car-following	54.5	8.8	37	78	12-84
Trust in lane changing	53.7	8.5	35	68	12-84
SSQ	29.1	28.5	0	112.2	0-236
PQ	93.0	14.8	50	120	19-133

Participants were also asked about their familiarity with automation technology and if they have any driver assistant features in their vehicle and how often they use these functions. The number of participants who indicated that they have not heard or only heard once, or twice about automated vehicles was very low (6 in total). Therefore, we merged the two groups under the name of “not familiar with automated vehicles”. As it can be seen in Figure 4-7(a), 24 out of the 48 participants are fairly familiar with automation technology and four participants work in a field directly related to CAVs. Figure 4-7(b) illustrates that 7 participants have ACC available on their car and only 4 of them use this feature very often. While only one person has automated lane change feature but he or she does not use it at all.

It should be noted that, trust in automation had a significant correlation with experience in using automated functionalities (correlation = 0.43, p-value 0.005). Thus, in the analysis we only considered trust in automation as a predictor of LMM models.



0: Not familiar with automated vehicles
1: Fairly familiar with the idea of automated vehicles;
2: Follow the developments of automated vehicles;
3: Work in a field directly related to automated vehicles.

CC: cruise control;
ACC: adaptive cruise control;
LKS: lane keeping system;
ALC: automated lane change.

Figure 4-7 Distributions of participants’ (a) familiarity with CAVs and (b) possession and usage of driver assistant features.

4.3.2 Driving behaviour descriptive statistics

The descriptive statistics of car-following speed is presented in Table 4-2. We have categorized the instantaneous speed based on the speed limit, driving mode, and lane type. As it can be seen, the mean driving speed in both speed limit categories is higher in automated mode, especially on DLs.

Table 4-2 Descriptive statistics of car-following speed

	Instantaneous speed (m/s)					
	Speed limit = 100kph			***Speed limit = 120kph***		
	Automated/DL	**Automated/NL**	**Manual/NL**	**Automated/DL**	**Automated/NL**	**Manual/NL**
Mean	95.99	93.18	91.95	108.97	98.96	97.54
Standard deviation	7.44	8.02	9.72	10.01	11.61	13.08

Next, the car-following observations for each mode of driving was derived for comparisons between scenarios. Longitudinal manoeuvres were divided into three different groups based on the size of THW: a) free flow when the THW is larger than 3s and the speed of the ego vehicle is not restricted by a lead vehicle, b) car-following when the THW is equal or smaller than 3s, and c) critical car-following when the THW is equal or smaller than 1.5s. The average THW during capacity conditions of Dutch freeways is approximately equal to 1.5s, which represents a capacity of 2.400 veh/hr/lane (Grontmij, 2015). Therefore, the THW≤ 1.5s was chosen as the critical THW from the aspect of capacity. Moreover, car-following with THWs around 1.5s, increases the driver’s perception of risk without making the driving task appear unrealistic (Tomasevic et al., 2022).

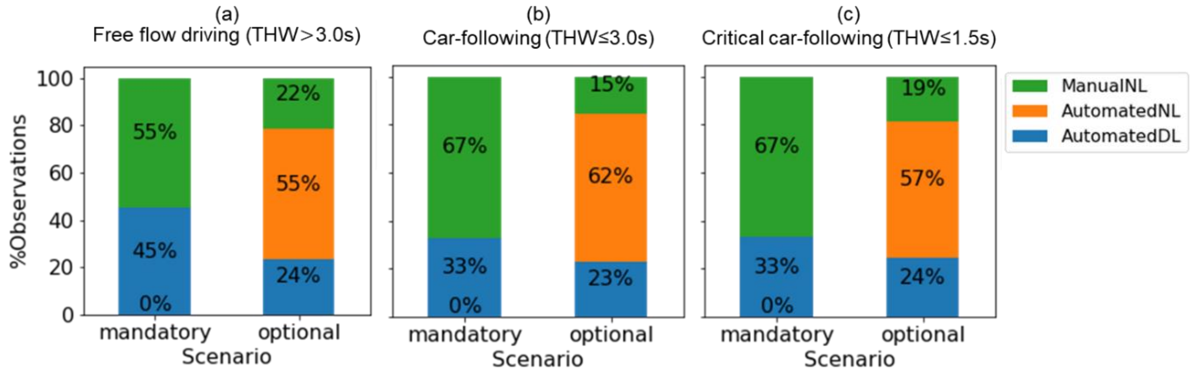


Figure 4-8 Car-following observations per driving mode in *Mandatory* versus *Optional* scenarios.

Figure 4-8 illustrates the car-following observations per driving mode. As it can be seen in Figure 4-8, the percentage of car-following observations in automated mode in *Optional* scenario (the sum of Automated/DL and Automated/NL) is higher compared to *Mandatory* scenario (Automated/DL) for all three car-following categories. This is because in *Optional* scenario the participants could choose between automated and manual mode on NLs, while in *Mandatory* scenario they could drive in automated mode only on the DL while on NLs they had to drive manually. So, on the segments without a DL, automated driving was not possible. In *Optional* scenario, where the participants could choose their driving mode, the percentage of automated observations is much higher than manual observations which shows that drivers preferred to use automation more often.

Table 4-3 Number of lane change manoeuvres per merge type in Mandatory versus Optional scenarios

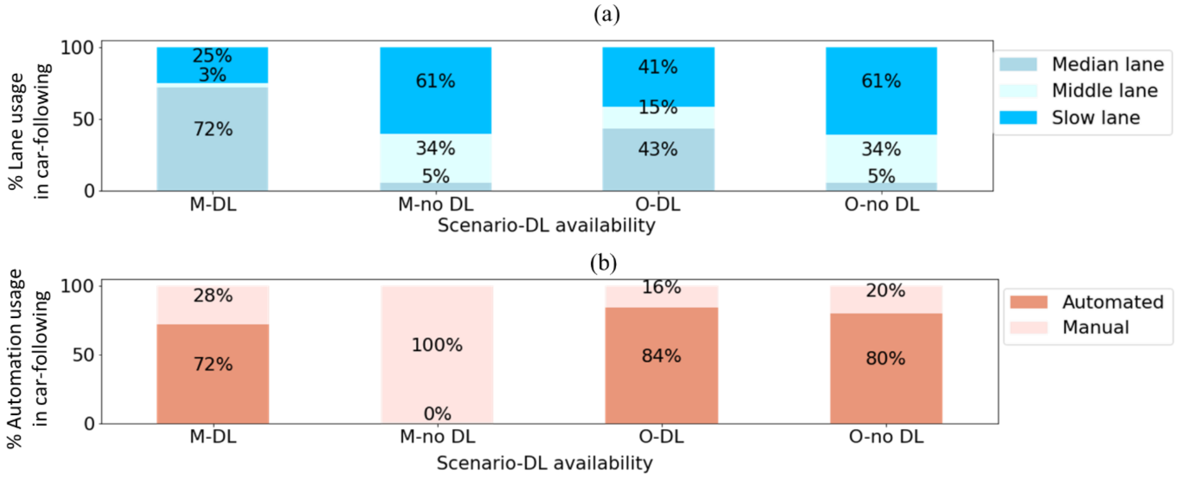
	Number of observations for Lane change manoeuvres							
	***Mandatory* scenario**				***Optional* scenario**			
	Automated/ DL	**Automated/ NL**	**Manual/ DL**	**Manual/ NL**	**Automated/ DL**	**Automated/ NL**	**Manual/ DL**	**Manual/ NL**
On-ramp	N/A*	4	N/A*	79	N/A*	46	N/A*	45
Off-ramp	N/A*	0	N/A*	2	N/A*	1	N/A*	3
Keep right	N/A*	62	N/A*	139	N/A*	125	N/A*	42
Overtake	56	11	13	91	56	54	5	28
Total	56	77	13	311	56	226	5	118

* Not Applicable

Table 4-3 shows the number of lane change manoeuvres per merge type in *Mandatory* versus *Optional* scenarios. One observation represents one lane change manoeuvre. The low number of off-ramp diverge gaps is due to the fact that the road signs showing the destination in the driving simulator were placed, following the Dutch road design guidelines, at 1200m, 600m, and right before the deceleration lane. So, the participants kept right before the deceleration lane began. Therefore, off-ramp diverge manoeuvres were excluded from the analysis. In *Mandatory* scenario, only those lane changes to the DL could be executed in automated mode, given that the participants were not allowed to drive in automated mode on NLs. However, 77 lane changes on NLs were executed in automated mode by mistake (i.e., drivers forgot to switch to manual mode on NLs in *Mandatory* scenario). On the other hand, in *Optional* scenario, where the participants were allowed to perform automated lane changes on any lane, the number of automated lane changes is higher compared to manual lane changes (about 70% of total lane changes were executed in automated mode). This shows that drivers are more inclined to change lane in automated mode, especially when keeping right or overtaking, while when merging from an on-ramp in *Optional* scenario they have no preferred mode.

4.3.3 The impact of DLs on the preference to use automation in car-following and lane change manoeuvres

Figure 4-9(a) shows the percentages of lane utilization in different segments of the road network depending on the availability of a DL and the scenario (*Mandatory* or *Optional*). The right most column shows the percentages of lane utilization in *Optional* scenario when there is no DL available (O-no DL). As it can be seen, drivers chose to drive mostly on the slow and the middle lane (61% and 34%, respectively). However, when a DL is available in the same scenario (second right column, O-DL), the participants drove more on the median lane which was a DL. So, the presence of a DL motivated the drivers to drive on the median lane. If the utilization of the DL is mandatory (left most column, M-DL), drivers are more likely to drive on the median lane (DL) since this is the only lane where they can drive in automated mode. However, in case of no DL (M-no DL and O-no DL), there is not much difference in lane usage (median, middle, or slow) between *Mandatory* and *Optional* scenario.



M-DL: Mandatory scenario on sections with a DL
M-no DL: Mandatory scenario on sections with no DL
O-DL: Optional scenario on sections with a DL
O-no DL: Optional scenario on sections with no DL

Figure 4-9 (a) Lane utilization and (b) preference of using automation in car-following (THW≤3.0s) based on scenario and DL availability.

Figure 4-9(b) illustrates the drivers' preference to use automation in the two scenarios and based on the availability of a DL. Obviously, in *Mandatory* scenario, when there is no DL (M-no DL), automation usage is 0% since the drivers were not allowed to use automation. In the same scenario, on the segments with a DL (M-DL), the participants drove 72% in automated mode on DLs and only 28% drove manually on NLs. In *Optional* scenario where drivers could choose between automated and manual modes, most of them preferred to drive in automated mode in car-following no matter whether a DL is available or not. Although the presence of a DL motivates the drivers to drive on the median lane (Figure 4-9(a), O-DL and M-DL), it does not influence their preference to use automation (Figure 4-9(b), O-DL and O-no DL).

Considering the lane change manoeuvres, Figure 4-10 illustrates the frequency of each driving mode for every merge type. It should be noted that the participants were instructed to change lane in automated mode when entering the DLs in both scenarios. They also were instructed to not drive in automated mode on normal lanes in *Mandatory* scenario. Thus, they could choose their lane change mode only on normal lanes in *Optional* scenario. Therefore, only manoeuvres executed on normal lanes in *Optional* scenario were considered in Figure 4-10. A total of 344 lane change manoeuvres were performed. Drivers preferred to perform automated lane-change when overtaking and when keeping right. While, at on-ramps there is a marginal difference between the percentages of manual and automated lane change (49% and 51%).

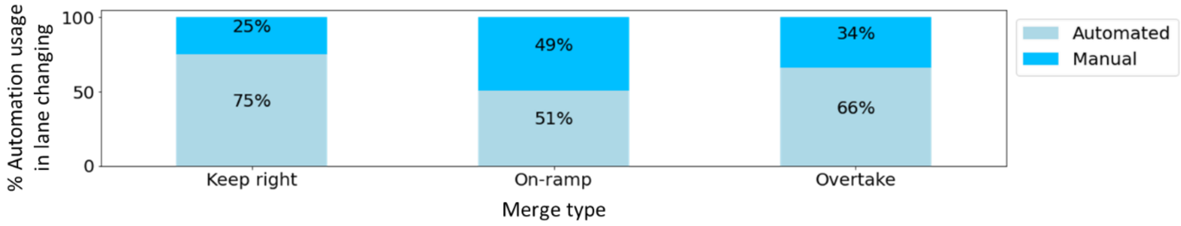


Figure 4-10 Preference to use automation based on merge type on NLs in Optional scenario.

We plotted the preference to use automation against the order of road segments that was driven in *Optional* scenario. The aim was to investigate if drivers adopted more automated lane change after they got used to the system. We only considered *Optional* scenario since the participants could choose automated lane change also on the segments without a DL (segments 1 and 3). Figure 4-11 reveals that the participants chose more automated lane change after they tried it on the first segment. However, no major differences were found between the 2nd, 3rd, and 4th segments.

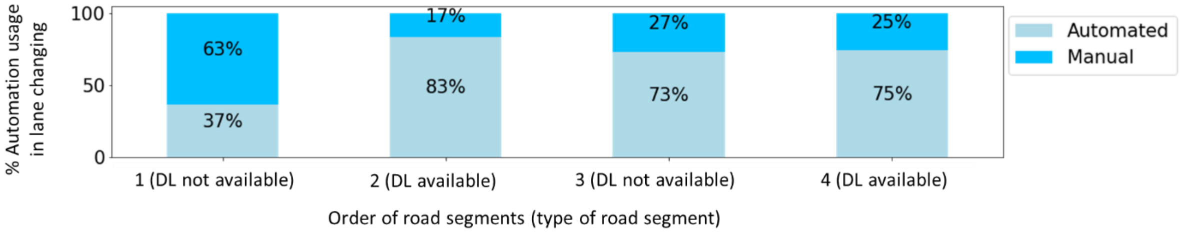


Figure 4-11 Frequency of automated lane changes in the different road segments in Optional scenario.

4.3.4 Linear mixed effects models (LMM)

Linear Mixed Effects Models (LMM) is a widely used method for the analysis of non-normal longitudinal data with random effects, where each subject has multiple observations (Wang et al., 2019; Razmi Rad et al., 2021). Different LMMs were estimated to explain drivers' preferences to use automation and the THW and merge gap size. First, we estimated LMMs to investigate the predictors of drivers' preference to use automation in car-following and lane changing, taking into account the driver characteristics such as the drivers' age, gender, education, familiarity with automation, trust, and experience in automation, derived from the questionnaires (Table 4-4 and Table 4-5). We only considered observations on NLs in *Optional* scenario since the drivers could not choose their driving mode in *Mandatory* scenario or on DLs. Second, we estimated two more LMMs to compare the car-following (THW$\leq$ 3s) and critical car-following (THW$\leq$ 1.5s) behaviour in different modes (automated vs. manual) and lane types (DL vs. NLs) taking into account the driver characteristics (Table 4-6). Third, three more LMMs were estimated to study the drivers' gap acceptance behaviour in on-ramp, keep right, and overtake manoeuvres, considering the driver characteristics as well as the size of the accepted merge gaps (Table 4-7). To study the THW and accepted gap (Table 4-6 and Table 4-7), all observations in both scenarios and both lane types were included. We considered a random intercept for each participant to capture correlations between the observations from the same person in all LMMs.

4.3.4.1 Preference to use automation in car-following

Table 4-4 presents the results of the LMM with binary outcome considering the observations on NLs in *Optional* scenario. On the one hand, drivers who are fairly familiar with CAVs or follow the developments, tend to use automation in car-following significantly more than those who are not familiar with CAVs. On the other hand, drivers who work in a field directly related to CAVs, prefer manual mode in car-following (Coefficient = -1.7076). Female drivers and drivers with post graduate education level are more likely to use automation. In terms of age effects, results show that middle aged (40-60) and old (60-80) drivers use automation in car-following significantly more, compared to younger drivers. Trust in automation in car-following also has a significant positive effect in drivers' preference to use automation. However, the coefficient shows only a marginal difference (0.0203).

Table 4-4 Drivers' preference to use automation in car-following in Optional scenario – LMM

	Categories	**Coefficient**	**p-value**	**Z**
Intercept		-0.2213	0.095*	-1.670
Familiarity	Fairly familiar vs. not familiar	0.1944	0.006**	2.749
	Follow CAV technology vs. not familiar	0.3919	<0.001**	5.674
	Work on CAVs vs. not familiar	-1.7076	<0.001**	-16.790
Gender	M=0 (vs. F=1)	-0.4297	<0.001**	-7.279
Education	Post graduate vs. Under graduate	0.8710	<0.001**	16.987
Age	40-60 vs 20-40	1.2662	<0.001**	21.641
	60-80 vs 20-40	0.4940	<0.001**	8.507
Trust		0.0203	<0.001**	7.922
Statistics				
Number of observations	17201			
Log-likelihood	-7791.4			
AIC	15594.8			

*Significant at 90% confidence level
**Significant at 95% confidence level

4.3.4.2 Preference to use automation in lane changing

To investigate drivers' preferences to use automation in lane changing manoeuvres, three LMMs with binomial outcome (automated/manual) were estimated considering lane change observations performed on NLs in *Optional* scenario (Table 4-5). The reason is that in other situations (*Mandatory* scenario or *Optional* on DLs) the drivers had to perform lane changes according to the instructions of the experiment. The dependent variable was the preference to use automation in lane changing. According to the results, the merge gap size was found to be a significant predictor of drivers' preference to use automation in overtaking and on-ramp merging manoeuvres. Additionally, older drivers (60-80 year old), preferred more automated overtaking compared to the younger age groups (Coefficient = 1.9829). For keep right manoeuvres, drivers who work in a field directly related to CAVs performed less automated lane changes (Coefficient = -2.3914). Other independent variables mentioned above (gender, education level, trust in automation in lane changing, and experience with automation technology) were not significant predictors of drivers' preferences to use automation in lane changing manoeuvres.

Table 4-5 Drivers' preferences to use automation in lane change manoeuvres – LMM

		Overtake			Keep right			On-ramp		
	Categories	Coef.	p-value	Z	Coef.	p-value	Z	Coef.	p-value	Z
Intercept		-3.0071	0.009**	-2.621	2.1401	0.004**	2.863	-2.9722	0.002**	-3.037
Familiarity	Fairly familiar vs not familiar				-0.8360	0.291	-1.057			
	Follow CAV technology vs not familiar				-1.1910	0.147	-1.450			
	Work on CAVs vs not familiar				-2.3914	0.008**	-2.653			
Age group	40-60 vs 20-40	0.7092	0.226	1.212						
	60-80 vs 20-40	1.9829	0.012**	2.512						
Merge gap (s)		0.9615	0.003**	2.958				1.0373	0.002**	3.125
Statistics										
Number of observations		82			167			91		
Log-likelihood		-45.53			-88.97			-57.2		
AIC		97.05			181.93			118.4		

**Significant at 95% confidence level

4.3.4.3 Car-following THW

In order to compare the car-following behaviour in different modes, an LMM was estimated considering THWs≤3.0s. As it can be seen in Table 4-6(a), THWs in manual mode are significantly (90% confidence) smaller than THWs in automated mode (coefficient = -0.119). On the other hand, if the automated driving takes place on a DL, drivers follow the lead vehicle more closely (coefficient = -0.159). We also included the instantaneous speed (m/s) as a continuous variable in the model. Results show that the participants keep significantly larger THW when driving faster. Another LMM was developed for critical car-following behaviour considering THWs≤1.5s. In line with the results for car-following (THW ≤ 3s), driving mode, lane type, and driving speed significantly affect the critical car-following (Table 4-6(b)).

Table 4-6 THWs for car-following - LMM

		(a)			(b)		
		Car-following (THW≤ 3s)			Critical car-following (THW≤ 1.5s)		
	Categories	Coefficient	p-value	Z	Coefficient	p-value	Z
Intercept		0.384	<0.001**	6.694	0.629	<0.001**	21.489
Driving mode	Manual vs. Automated	-0.119	0.052*	-1.942	-0.086	0.008**	-2.643
Lane type	DL vs. NL	-0.159	<0.001**	-21.364	-0.058	<0.001**	-12.401
Speed		0.050	<0.001**	48.633	0.019	<0.001**	28.706
Statistics							
Number of observations		47664			23034		
Number of participants		48			48		
Log-likelihood		-39076.18			1335.94		
AIC		78160.36			-2663.88		

*Significant at 90% confidence level
**Significant at 95% confidence level

4.3.4.4 Gap acceptance in lane changing

Three LMMs were estimated to investigate the effects of scenario variables and demographics on the accepted lane change gaps. According to Table 4-7, driving mode influences the size of the accepted gap. In all types of lane changes (on-ramp, overtaking, keep right), the accepted gap is smaller in manual mode as shown in Table 4-7. Obviously, lane type is not included in the models for keep right and on-ramp merging gaps since the lane which the driver merges into is always a normal lane in these manoeuvres. However, in overtake manoeuvres, when changing lane towards DLs, the drivers accepted smaller merge gaps (coefficient = -0.444). Age was also found to affect the overtaking merge gaps in manual mode. Contrary to expectations, older drivers (60-80) accepted significantly (at 90% confidence level) smaller gaps when overtaking manually compared to young age group (20-40). However, there is no significant difference in accepted gaps in automated mode over different age groups. The small accepted merge gaps by older drivers in manual mode could be because of their poor performance in the driving simulator. The higher SSQ score of older participants (37.03) compared to middle aged and younger ones (25.3 and 28 respectively) can also corroborate on this.

Table 4-7 Accepted gaps for lane changing - LMM

		On-ramp			**Overtake**			**Keep right**		
	Categories	**Coef.**	**p-value**	**Z**	**Coef.**	**p-value**	**Z**	**Coef.**	**p-value**	**Z**
Intercept		3.171	<0.001**	26.750	3.430	<0.001**	22.350	2.587	<0.001**	27.328
Driving mode	Manual vs. Automated	-0.530	<0.001**	-3.955	-0.623	0.001**	-3.301	-0.125	0.081*	-1.746
Lane type	DL vs. NL				-0.444	<0.001**	-3.889			
Age*Driving mode	Automated, 40-60 vs 20-40				-0.183	0.311	-1.013			
Age*Driving mode	Manual, 40-60 vs 20-40				0.097	0.603	0.520			
Age*Driving mode	Automated, 60-80 vs 20-40				-0.256	0.186	-1.322			
Age*Driving mode	Manual, 60-80 vs 20-40				-0.379	0.071*	-1.804			
Statistics										
Number of observations		174			314			368		
Number of participants		48			48			48		
Log-likelihood		-209.52			-400.0			-693.45		
AIC		423.04			808.0			1390.9		

*Significant at 90% confidence level
**Significant at 95% confidence level

4.4 Discussion

In this paper, we presented findings on the impacts of the presence and utilization policy of a dedicated lane on drivers' preference to use automation as well as their behaviour in car-following and lane changing on motorways.

4.4.1 Drivers' preference to use automation in car-following

The presence of a DL motivated the drivers to drive more on the fast lane which was the DL, especially in *Mandatory* scenario, since the fast lane was the only lane that they could drive in automated mode. However, no significant difference was found in the preference of drivers to use automation in car-following in segments with and without a DL for *Optional* scenario, where participants could drive in automated mode on all lanes. On the other hand, the LMM revealed other predictors of automation use in car-following. Drivers who work in a field directly related to CAVs preferred less automated car-following. This could be because people who work on this field are more aware of the limitations of this technology and may not trust the system. However, we could not confirm a significant correlation between familiarity and trust. It could also be related to the very small number of participants who work in a field directly related to CAVs (4 participants). Thus, further investigations are needed in this regard. Besides, female drivers were more likely to use automation in car-following than males. This is in line with the findings of Piao et al. (2005) that revealed that female drivers appreciate the high level of security provided by automation, because they are less confident in controlling their speed or care more about speed control compared to males. Confirming the results of Kadylak et al. (2021) and Nielsen and Haustein (2018), stating higher education has a positive impact on acceptance of automation technology, this study suggests that drivers with post graduate educations were more likely to use automation in car-following. We also found age as a significant predictor of automation use in car-following. Middle aged drivers were most likely to use automation while younger drivers used automation less than other age groups. The reason could be the fact that young drivers are more confident in their driving skill and less interested to be assisted by automation (Piao et al., 2005). Moreover, three out of four participants who worked on CAVs (with less interest in automation use) were in the young age group.

4.4.2 Drivers’ preference to use automation in lane changing

During the drives in the driving simulator, participants changed lanes at on- and off-ramp, to overtake, and to keep right. We excluded the off-ramp lane changes since there were only six observations, too little for a meaningful analysis. For the other three types of lane change, we considered observations in *Optional* scenario and on normal lanes, where the drivers could choose their driving mode in lane changing.

Based on the results, 66% of overtaking manoeuvres were performed in automated mode. Moreover, the LMM showed that interest in automated lane change increased with age. Older drivers (60-80 years old) were most likely to prefer automated mode in overtaking manoeuvres. This result corroborates the findings of Nordhoff et al. (2018), that suggest that older drivers express higher intention to use automated shuttle busses. Also, Rödel et al. (2014) and Piao et al. (2005) found that older drivers show more positive attitude towards using highly automated vehicles and are more interested in buying driver assistance features, as it facilitates safe and comfortable driving. However, a possible reason for higher interest of older drivers in automated lane change could relate to their higher simulation sickness. They might have been feeling not good enough to resume manual control. On the other hand, the low interest of young drivers in automated lane change, could be explained by the lower lateral speed in automated mode. The mean lateral speed in overtaking in automated mode was 0.005 m/s with a standard deviation of 0.022. This is very much lower than young drivers’ average manual lateral speed in overtake which is 0.028 m/s with a standard deviation of 0.047, and closer to the older drivers’ lateral speed in manual mode (0.014m/s with a standard deviation of 0.017). Thus, automated lane change with lower lateral speed was more preferred by older drivers than by younger ones. Thus, further investigations are needed regarding the effects of age on automation use. The presence of a larger gap was another significant predictor of automation use in overtaking.

Regarding keep right manoeuvres, drivers mostly preferred to change lane in automated mode (75% in automated mode). Those who work on CAVs preferred less automated lane changing in keep right manoeuvres, in line with car-following.

Considering on-ramp merges, the percentages of automated and manual lane changes were very close (49% automated and 51% manual). However, in line with overtaking manoeuvres, the LMM model revealed that the presence of a larger gap is a significant predictor of automation use.

4.4.3 Drivers' behaviour in car-following and lane-changing

It was also investigated if drivers adopt shorter time headways and merging gaps when driving in automated mode compared to manual mode. LMMs compared the THWs and merging gaps in car-following and lane changing while in automated and manual mode and revealed that drivers tend to follow a lead vehicle keeping larger THWs and merge into larger gaps in automated mode. This would have positive impacts on traffic safety but might deteriorate traffic efficiency. Accepting larger THWs and merge gaps in car-following and lane changing in automated mode could be due to the drivers' choice of when to use automation as well. For example, when it is crowded and surrounding vehicles are too close, driving can be more complex and drivers might prefer to take control of the vehicle (Tomasevic et al., 2022) and switch to automation when it is less crowded. Thus, the THWs and accepted gaps are larger in less crowded situation. It can also be related to the fact that drivers tend to take less risk and keep larger THWs and merging gaps when they are not in control of driving (Horswill and McKenna, 1999). This is in line with the findings of Basu et al. (2017), that suggest that drivers expect a significantly more defensive driving style from the automated vehicle. It also confirms the results of the previous studies on car-following in ACC mode (Kessler et al., 2012; Bianchi Piccinini et al., 2014; Schakel et al., 2017).

We also aimed to compare the THW and merging gaps on dedicated lanes and normal lanes when driving in automated mode. According to the results, drivers kept shorter time headways when they were driving on dedicated lanes and accepted smaller gaps when changing lane towards the dedicated lane, knowing that all vehicles are automated. This corroborates the results of the driving simulator study by Trende et al. (2019) that reported that drivers show less conservative behaviour when interacting with an automated vehicle compared to a manual vehicle, by higher probability of gap acceptance at intersections. A field test by Soni et al. (2022) also indicated that drivers adopt smaller gaps if the approaching vehicle is known to be automated.

4.5 Conclusions and future work

The aim of this paper was to investigate the effects of the presence and utilization policy of a dedicated lane on drivers' preference to use automation as well as their behaviour in car-following and lane changing on motorways. The results of this study can be used as a fundamental for more realistic traffic simulations reflecting the impacts of a dedicated lane on the behaviour of CAV drivers.

The results show that the presence of a dedicated lane does not increase the preference of driving in automated mode. However, a dedicated lane, especially with mandatory utilization, motivates the drivers to drive on the median lane (the only dedicated lane) more often. Thus, the mandatory utilization could be a suitable policy for the early stage of implementing dedicated lanes to facilitate platooning, given that the access to these lanes is continuous, to avoid too many lane changes near the beginning and ending of the dedicated lanes. Additionally, we found that lateral speed in lane changing is an important factor for drivers' preference to use automation. Older drivers used more automation in lane changing. This could be because the lateral speed was closer to their preferred manual lateral speed. So, the lateral speed could be another adjustable parameter in automated mode to address the needs of wider range of drivers. Furthermore, trust in automation turned out to be effective on drivers' preference to overtake in automated mode. So, it is recommended to investigate the impact of trust, as well as educating people about automated vehicles, on drivers' preference to use automation in the long term.

This study further gave insights into drivers' behaviour in car-following and lane changing with regard to the driving mode and the availability of a dedicated lane. Based on the results, drivers take less risk in automated mode and in mixed traffic, at least during the short experience with automated vehicles. This should be considered by traffic simulation studies to more realistically calculate the capacity and delay, at least for a short term after the deployment of the novel technology. It is also recommended to investigate the car-following and lane changing behaviour in automated mode in the long-term, when risk perception decreases over time and experience (Brell et al., 2019). On the other hand, drivers tend to follow their leaders more closely and merge into smaller gaps on dedicated lanes, knowing all vehicles are automated. Another finding regarding the impacts of the dedicated lane pertains to driving speed. Drivers tend to drive faster on the dedicated lanes compared to the normal ones that might raise a safety concerns. This speed difference between the two lanes increases the risk of collision when changing lane. To reduce this collision risk, automation of all lane changes towards and from the dedicated lanes is essential.

In this study a market penetration rate of 40% was assumed. So, it would be relevant to see how an increase in the market penetration rate affects the behaviour of CAV drivers in mixed traffic. We chose a virtual reality environment instead of a field test due to technical and ethical reasons. Although a driving simulator experiment makes it possible to systematically vary the variables of interest, the real-world impacts of automation and dedicated lanes on the behaviour of CAV drivers remains a question to be answered in future research. Besides, we measured driver behaviour in the two modes and lane types over a limited time and at one market penetration rate. So, it would be relevant to test the long-term effects of automation and dedicated lanes at different market penetration rates, conducting field tests in future studies.

Chapter 5

Discussion, Conclusions and Recommendations

This thesis firstly reviewed the literature to reveal the key factors in design and operation of DLs, considering traffic efficiency and safety, market penetration rate (MPR) of automated and/or connected vehicles (C/AVs), and human factors. It also provided an agenda for future research in this regard. Secondly, this thesis studied the impacts of the presence of a DL on the behaviour of drivers of MVs and CAVs in car-following and lane changing manoeuvres. Chapter 1 outlined the research framework and formulated the scientific research questions, which were answered throughout Chapters 2-4.

This chapter discusses the main research findings, highlights their practical implications and gives recommendations for future work. Section 5.1 discusses the scientific findings and presents the answers to the research questions. Section 5.2 presents the overall conclusions. Section 5.3 describes the relevance of the research findings to practice and points out the possible future actions for road authorities. Section 5.4 discusses the research limitations of this study and provides directions for future studies.

5.1 Scientific findings and discussion

The main objectives of this dissertation were (1) to develop a conceptual framework that identifies the knowledge gaps and provides a research agenda on design and operation of DLs; (2) to investigate the impacts of the presence of a DL on the behavioural adaptation of MV drivers in car-following and lane changing; and (3) to study the impacts of the presence and utilization policy of a DL on CAV drivers' preference to use automation as well as their car-following and lane changing behaviour. To address these objectives three research questions were investigated in this thesis. In the following, the main findings are presented by answering the research questions formulated in section 1.3.

What are the underlying factors that influence the design of dedicated lanes? To what extent are these factors addressed in the literature and what are the challenges for future research?

To answer this research question, Chapter 2 provided a comprehensive overview of the literature to develop a conceptual framework accounting for the factors that could affect the safety and efficiency of DLs (Figure 5-1). This conceptual framework was underpinned based on relevant literature on how the deployment of C/AVs, driver behaviour, and DL design and operation affect traffic safety and efficiency. According to the review, the literature has mostly focused on the impacts of DLs on traffic efficiency considering longitudinal automation, without considering the automation and connectivity in transient manoeuvres. Regarding the driver behaviour, there is limited research on the impacts of DLs on the behavioural adaptation of MV and C/AV drivers. Also, research is needed to investigate if this behavioural adaptation has positive or negative effects on traffic performance. Considering the design of DLs, the literature lacks studies on clear and comprehensible signage and demarcations and their impact on driver behaviour and traffic performance.

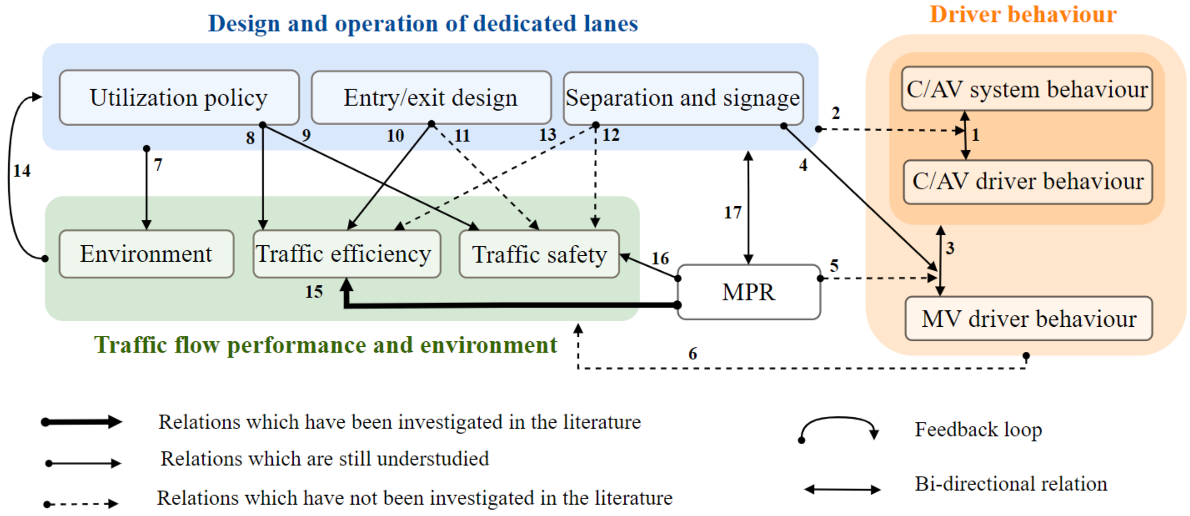


Figure 5-1 The conceptual framework.

Based on the review, the developed conceptual framework identified the relations which were studied (bold solid arrows), those that are understudied (solid arrows), and those that are not yet addressed in the scientific literature (dashed arrows). Based on this conceptual framework, a research agenda on design and operation of DLs for C/AVs was proposed.

Regarding the DL design, the research agenda emphasizes the need for specifying the vehicle types (i.e. automation functionalities) to be allowed on DLs and the importance of clear and comprehensible signage and demarcations for such lanes to mitigate and prevent errors or violations by drivers. The research agenda further emphasizes the need for understating the behavioural adaptation of MV and C/AV drivers considering the impacts of different MPRs and incorporating this empirical data to driving simulators and traffic flow simulation models for a robust evaluation of these lanes. It is also recommended to consider automation of lateral control by developing automated lane change algorithms, taking into account connectivity/cooperation between CAVs and possibly also between CAVs and MVs in future traffic simulation and driving simulator studies.

The research agenda also served as a basis for defining the remaining two objectives of this thesis including the empirical studies to gain insights on MV and CAV drivers' behaviour in mixed versus separate traffic (via DLs). These objectives pertain to arrows 1, 2, 3, and 4 in the conceptual framework, which were addressed by answering the following two questions:

What is the impact of the presence of a dedicated lane for CAVs on the behavioural adaptation of MV drivers in car-following and lane changing (arrows 3, and 4 of the conceptual framework)?

To answer this research question, a driving simulator experiment was conducted to examine the behavioural adaptation of MV drivers in car-following and lane changing in mixed traffic and compare that to the situation where CAVs are separated from MVs via DLs (Chapter 3).

The car-following time headways (THWs) and the accepted merging gaps by participants were compared when driving in three different scenarios, namely (1) *Base*, where only MVs were present in traffic, (2) *Mixed*, where platoons of CAVs drove on any lane and mixed with MVs, (3) *DL*, where platoons of CAVs drove only on a DL. A very short intra-platoon THW (0.3s) was chosen for the CAVs to see if behavioural adaptation happens to MV drivers with a very close car-following of CAVs. This was especially considered regarding the Mixed scenario to see if it is safe to have CAVs mixed with the traffic before we can implement DLs. The results showed that there is no significant difference in the driving behaviour between *Base* and *Mixed* scenarios at the tested MPR. However, in the *DL* scenario, MV drivers drove closer to their leader specially when driving on the middle lane next to the platoons and accepted up to 12.7% shorter gaps in lane changing manoeuvres.

In the mixed traffic situation, CAV platoons' exposure time (the time when driving next to a platoon) is too short to influence the behaviour of MV drivers. Moreover, at moderate MPRs of CAVs, the number and size of the CAV platoons, and consequently their conspicuity is very low. Thus, as suggested in the literature, the behavioural adaptation is less likely to happen at lower exposure time and conspicuity of platoons (Gouy et al., 2014). However, dedicating a lane to CAVs increases the density of CAV platoons on one lane and consequently their conspicuity becomes higher. As a result, MV drivers are more influenced by CAV platoons on a DL which is reflected in adopting shorter THWs and gaps in car-following and lane changing, respectively. These results seem to be consistent with previous findings investigating the behavioural adaptation of MV drivers when driving next to CAV platoons (Schoenmakers et al., 2021; Gouy et al., 2014; Gouy et al., 2013). This insight provides empirical foundation to increase the realism of future microscopic traffic flow models (Farah et al., 2022; Calvert, 2017). However, field tests are needed to corroborate these findings.

What are the impacts of the presence and utilization policy of a dedicated lane on CAV drivers' preference to use automation as well as their car-following and lane changing behaviour (arrows 1, and 2 of the conceptual framework)?

The next research gap that was revealed based on the literature review in Chapter 2 pertains to the impacts of the presence and utilization policy of a DL on CAV drivers' interactions with the automation system. To fill this research gap, a second driving simulator experiment was conducted including two scenarios: a) *Mandatory* scenario: in which the median lane of the motorway was dedicated to CAVs and automation was only allowed on this lane; b) *Optional* scenario: in which using the DL was optional, meaning that participants could drive in automated mode on any lane. Under the automated mode the participants could adjust the speed and THW and initiate automated lane changes.

CAV drivers' preference to use automation in car-following and lane changing was assessed. The results reveal that the presence of a DL has no significant impact on drivers' preference to use automation. However, the DL, especially with mandatory utilization was found to motivate the drivers to use the median lane (the DL) of the motorway more often. This is because the drivers prefer to drive on the slow or the middle lanes as indicated in the questionnaire. So, when automation is available on all lanes, they keep driving on the slow or the middle lane in automated mode. However, when automation is not available on the slow or the middle lanes, they have to switch to the median lane (the DL) to perform automation.

Additionally, the THWs in car-following and accepted gaps in lane changing between the two driving modes and lane types (i.e., normal vs. dedicated lanes) were compared. The results showed that drivers tend to keep 7.5% larger THWs and merge into larger gaps (19%, 22%, and 5% in on-ramp, overtake, and keep right manoeuvres respectively) when driving in automated mode and in mixed traffic. On the other hands, drivers adopt 10% smaller THWs and up to 10% higher speed on DLs (in automated mode and a speed limit of 120kph) and accept 15.7% shorter gaps when changing lane towards the DL for an overtake, knowing that all vehicles are operating in automated mode.

Adopting larger THWs and gaps in automated mode confirms the findings of previous research by Basu et al. (2017) which suggest drivers prefer a more defensive driving style from automation. It can also explain drivers' choice of taking less risk in automation (Horswill and McKenna, 1999) or using automation when it is less complicated (Tomasevic et al., 2022). This would have positive impacts on traffic safety but might deteriorate traffic efficiency. On the other hand, adopting smaller THWs on DLs and accepting shorter gaps when changing lane towards a DL confirms the findings of previous studies suggesting drivers show less conservative behaviour when interacting with CAVs (Trende et al., 2019; Soni et al., 2022).

5.2 Overall conclusions

The first conclusion of this thesis is that to design and evaluate dedicated lanes for CAVs, factors indicated in the conceptual framework and their relationships should be taken into account to maximize the benefit provided by such lanes. Thus, according to the conceptual framework, the combined effects of traffic performance, driver behaviour, and DL design and configurations considering different MPRs of CAVs should be taken into account to evaluate such lanes. This requires understanding the behavioural adaptation of MV and C/AV drivers in both longitudinal and lateral movements, in relation to automation and different DL design configurations and incorporating this insight in traffic flow simulation models to evaluate the safety and efficiency implications of DLs.

Secondly, it can be concluded from the literature review in Chapter 2, that the MPR on its own cannot reflect the true adoption rate of automation mode. This is because traffic simulation studies suggest that DLs improve the traffic performance from a certain range of MPR (Madadi et al., 2021; Xiao et al., 2020). At the same time, behavioural studies on transitions of control reveal that drivers prefer to take control of the driving tasks in certain situations such as approaching a slower leader or when expecting vehicles will cut in (Varotto et al., 2017). Also, the results of the second driving simulator experiment in Chapter 4 suggest that CAV drivers do not use the automation to perform the entire driving task. Given these findings, to evaluate the impact of automation and dedicated lanes, the usage rate of automation should be taken into account, instead of the MPR. That needs to be considered in traffic simulation studies.

Thirdly, DLs do not decrease the possibility of behavioural adaptation of drivers of MVs. In fact, due to higher conspicuity of CAVs on a DL, such lanes increase the possibility of behavioural adaptation of manual vehicle drivers by close car-following and accepting smaller gaps in lane changing. This behavioural adaptation is not necessarily considered negative if it is not leading to risky manoeuvres which a human driver is not able to control. In fact, adopting shorter THWs (in manageable range by a human) in car-following can increase the capacity of the normal lanes on motorways, but requires equipping the manual vehicle fleet with driver assistance functions (i.e., collision avoidance) to avoid risky situations. Also, the DLs increase the chance of adopting smaller THWs in automated mode on these lanes which can increase the capacity of the DLs. In conclusion, DLs have the potential to increase the capacity of the motorways. However, when it comes to traffic safety, implementing such lanes without taking additional measures could lead to risky situations. These measures include a) proper and comprehensible signage and demarcations to avoid confusions for drivers of both MVs and CAVs; b) equipping the manual vehicle fleet with systems such as collision avoidance to avoid very close car-following to control the behavioural adaptation when driving next to platoons; and c) recommending automated lane changes to and from the DLs to decrease the risk of collision due to the difference in driving speed on normal and dedicated lanes.

5.3 Implications for practice

The findings of this thesis are relevant for policy-makers, traffic flow modellers, and road designers interested in evaluating the impacts of DLs on traffic performance, taking into account driver behaviour. The results are also relevant to car manufacturers interested in developing C/AVs that meet the needs of a wider range of drivers. This section discusses the practical implications of these findings for relevant stakeholders.

For *policy makers*, this thesis provides assessments on possible strategies for implementing DLs for CAVs based on the empirical data collected from the two driving simulator experiments. These strategies entail under which utilization policy the provision of DLs at moderate MPR can offer benefits for all traffic.

The driving simulator conducted in Chapter 3 examined the behavioural adaptation of MV drivers and revealed that MV drivers do not adapt their behaviour in mixed traffic without a DL at an MPR of 43%. On the other hand, microsimulation studies suggest that implementing DLs would improve the traffic efficiency when the MPR of CAVs reaches to a lane saturation level which is around 30%-50% (Ivanchev et al., 2017; Madadi et al., 2021; Xiao et al., 2020). Thus, implementing DLs can wait until reaching a moderate MPR from the aspect of safety and efficiency. Chapter 3 further showed that concentrating the CAVs on a DL increases their conspicuity, and consequently leads to behavioural adaptation of MV drivers (at least in the short term). MV drivers imitated the behaviour of CAVs by adopting smaller THWs which can be unsafe for a human driver. Thus, equipping MVs with systems such as collision avoidance to avoid close car-following by the time we accommodate CAV platoons on our road network, is essential to avoid risky manoeuvres.

Furthermore, two different utilization policies for DLs, namely *Mandatory* and *Optional,* were tested in the driving simulator experiment in Chapter 4. Results revealed that implementing a DL with mandatory utilization policy, meaning that automation is only allowed on DLs, increases the probability of driving on the median lane (the only lane for automated driving). This result suggests that mandatory utilization policy of a DL is suitable for the early stage of implementing DLs. Because on the one hand it facilitates platooning of CAVs by concentrating them on the DL. On the other hand, it reserves the other traffic lanes (normal lanes) for manual vehicles. In such a situation, a continuous access is recommended for the DLs to avoid too many mandatory lane changes right after the beginning and before the ending of the dedicated lanes.

Moreover, the results of the same experiment (Chapter 4) showed that although the presence of a DL does not increase the chance of driving in automated mode at the tested MPR (40%), it increases the probability of adopting smaller THWs when in automation which is beneficial for traffic efficiency.

For *traffic flow modellers,* this thesis provides empirical foundation to increase the realism of microscopic traffic flow models. The driving simulator experiment in Chapter 3 also tested the impacts of DLs on the behavioural adaptation of MV drivers. Results from this experiment showed that MV drivers adapt their behaviour by keeping smaller THWs in car-following and accepting shorter gaps in lane changing manoeuvres when driving next to DLs where CAV platoons drive. In addition, the second driving simulator experiment (Chapter 4) investigated CAV drivers' preference to use automation as well as the impacts of DLs on their driving behaviour. Results concluded that CAV drivers keep larger THWs and accept larger merging gaps when driving in automated mode and in mixed traffic, at least during the short experience with automated vehicles. However, they follow cars more closely on DLs and accept smaller gaps when changing lane towards DLs. The empirical findings from these chapters, that describe the behaviour of drivers of MVs and CAVs, can be incorporated into existing traffic flow models for evaluating the performance of DLs. This is essential to evaluate the impacts of automated driving and dedicated lanes more realistically.

For *infrastructure designers*, this thesis designed road signs for DLs and investigated the impacts of demarcations and location of such lanes. Based on a survey on symbol comprehension, a road sign was designed and proposed to inform the CAV and MV drivers about the DLs. Also, a buffer separated demarcation was used to separate the DL from the normal lanes. Despite the road signs, demarcations, and the instructions from the experimenter, the participants still made mistakes by driving in manual mode on DLs and automated mode on normal lanes in *Mandatory* scenario (this observations were excluded from the analysis). Thus, more effort is needed, at least in the short term after DLs implementation, to inform drivers about the usage of these lanes (i.e., in-vehicle message).

This thesis further gives insights regarding the location of DLs. Dedicating the median lane of the motorway to CAVs with a mandatory utilization policy reduced drivers' preference to use automation marginally. This is because drivers are mostly comfortable with driving on the slow or the middle lane. Thus, when automation was only allowed on DLs (the median lane), CAV drivers preferred to continue in manual mode probably because they preferred to drive on slow and middle lanes where automation is not allowed.

For *car manufacturers* this thesis provides guidance by revealing the impact of lateral speed on drivers' preference to use automation in lane changes. Based on the results of the experiment in Chapter 4, older drivers performed more automated lane changing compared to younger ones. This could be because the lateral speed in automated mode was closer to their preferred manual lateral speed. This finding suggests that being able to adjust the lateral speed could increase the preferences of CAV drivers to use automation. This suggestion can help car manufacturers to design CAVs with adjustable lateral speed to address the needs of wider range of drivers and consequently increase driving in automated mode.

5.4 Limitations and recommendations for future research

This thesis has contributed to the understanding and evaluating the impacts of dedicating a lane to CAVs on the behaviour of drivers of CAVs and MVs.

The limitations of the conducted research are related to the sample of participants, the data collection method, and the experimental design. In this section, several recommendations for future research are formulated that can build on the work presented in this thesis.

The participant sample in Chapter 3 consisted of young, highly educated individuals and the participant sample in Chapter 4 was dominated by male drivers. That means that generalization to other populations should be done with care. Future studies should be carried out with a larger sample of participants which is representative of the driver population.

In Chapter 4, drivers' preference to use automation was tested. However, the participants were drivers with or without interests in automation technology and are not necessarily representative of the CAV driver population of the future. This is because people who pay for automation functionality are probably more inclined to use this technology. Thus further investigations are needed regarding the preferences of drivers in using automation mode while hiring participants who are willing to pay for automation and own such a vehicle.

A virtual reality environment was chosen instead of a field test due to technical and ethical reasons. The added value of virtual reality is its controllability. The scenarios could be repeated exactly to the different participants, which comes at a cost of realism and complexity. Participants might adapt their behaviour knowing that they are being monitored and tested. Also, due to the controlled nature of the driving simulator, the participants do not experience any real risk (de Winter et al., 2012; Daamen et al., 2014). It is recommended to have some or all participants drive the Base scenario in a real field test and compare their results with those of the driving simulator to validate the results of the driving simulator. Also, Research is needed to examine the possibilities of conducting real world field test with CAV platoons on dedicated lanes.

The findings presented in this thesis relate to the short-term effects of behavioural adaptation as the participants did not have prior experience interacting with or operating a CAV and the durations of the experiment runs were limited to a short period of time (6-15 minutes). Also, the concept of DLs was introduced to the participants right before the experiment runs which together with automated driving could be too much information for participants. Moreover, the surrounding traffic in the driving simulator experiments included 40% CAVs with SAE level 4 and 5 with the same driving style. While, the future traffic will be composed of different automation levels and human drivers could influence the driving style of CAVs based on their preferences. Thus, the results show the impacts of dedicated lanes on the behaviour of human drivers in the initial phase of implementing dedicated lanes at around 40% MPR of CAVs with SAE level 4 and 5 with full adoption rate of automation and a unique driving style.

The human driver behaviour in relation to automation and dedicated lanes is still understudied, and consequently much additional research is needed. Moreover, the dedicated lanes are supposed to host C/AVs. However, it is still unclear what SAE levels (i.e. automation functionalities) are allowed on such lanes. Also, further research is needed on design, demarcations, and signage of DLs as well as how to educate and inform drivers about the usage of these lanes.

Finally, it is recommended to implement the empirical data from the driving simulators to the traffic flow models to more realistically evaluate the impacts of automation and DLs on traffic performance. Currently, the DLs for CAVs do not exist in motorway networks. Therefore, creating such lanes to conduct field tests with real traffic is not feasible. So, the DLs have been mostly evaluated from the aspect of safety and efficiency conducting microscopic simulation studies. Thus, the challenge is to change and adapt the current behavioural models in simulations to reflect as realistically as possible the behaviour of the different types of vehicles (MVs and C/AVs). This requires conducting driving simulator experiments and field tests, when possible, to understand the behaviour of MVs and C/AVs when interacting with each other in the presence of DLs, and incorporating this empirical data to traffic flow simulation models for a robust evaluation of these lanes.

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Summary

Dedicated lanes (DLs) have been proposed as a potential scenario for the deployment of connected and automated vehicles (CAVs) on the road network. However, knowledge on the design and operation of DLs and their impacts on the behaviour of drivers of CAVs and manual vehicles (MVs) is lacking in the literature. Therefore, this thesis investigated the following two questions:

(1) What are the underlying factors in design and operation of DLs and what are the relations between these factors?

(2) What is the impact of a DL on the behaviour of CAV and MV drivers?

Answering these two questions are critical for decision making on how to accommodate CAVs on our road network.

To answer the abovementioned questions, a two-step approach was followed. First of all, a review of the literature was conducted to develop a conceptual framework, which can be seen in Figure 1. The framework consists of the relations between driver behaviour, design and operation of DLs, and the traffic flow performance and environment. These are the three main components identified taking into account the market penetration rate (MPR) of automated and/or connected vehicles (C/AVs). The developed conceptual framework identifies based on the literature, the relations which were studied (bold solid arrows), those that are understudied (solid arrows), and those that are not yet addressed in the scientific literature (dashed arrows). Based on the conceptual framework and the identified knowledge gaps an agenda for research is proposed. More specifically the research agenda emphasizes the need for specifying the vehicle types (i.e. automation functionalities) to be allowed on DLs, the need for understating the behavioural adaptation of MV and C/AV drivers considering the impacts of different MPRs, and the importance of demarcations and signage. It is also recommended to develop automated lane change algorithms, taking into account connectivity between C/AVs which can be also implemented in driving simulators and traffic flow simulation platforms. Finally, it is recommended that future research investigate the combined effects of traffic safety and efficiency in designing DLs while considering driver behaviour adaptation and control transitions between manual and automated operation.

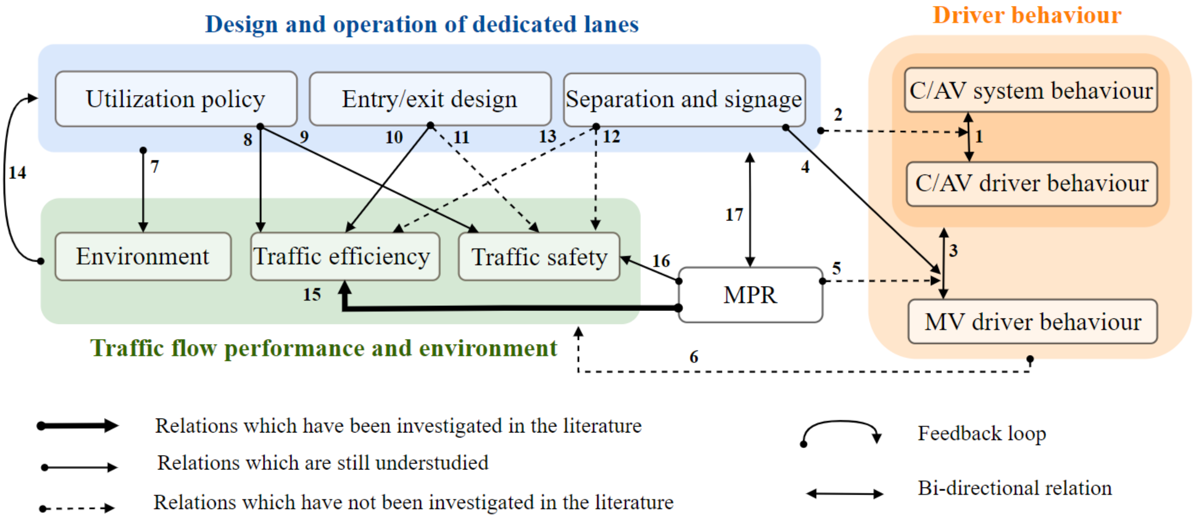


Figure 1 The conceptual framework for the relations between the design and operation of dedicated lanes, driver behaviour, traffic flow performance and the environment.

The conceptual framework served as a basis for the second step including empirical studies to gain insights on MV and CAV drivers' behaviour in mixed versus separate traffic (via DLs). A set of driving simulator experiments was used to provide observational data on driver behaviour.

The first driving simulator experiment focused on investigating the behaviour of MV drivers in mixed traffic on a road without a DL, and comparing that to the situation where MV drivers drive on a lane adjacent to a DL where CAV platoons drive. Fifty-one participants were asked to drive an MV on a 3-lane motorway in three different traffic scenarios, in a fixed-base driving simulator: (1) ***Base***, only MVs were present in traffic, (2) ***Mixed***, platoons of 2–3 CAVs drove on any lane and mixed with MVs, (3) ***DL***, platoons of 2–3 CAVs drove only on a DL. The DL was recognizable by road signs and a buffer demarcation which separated this lane from the other lanes. A moderate penetration rate of 43% was assumed for CAVs.

During the drives, the car following time headways (THWs) and the accepted merging gaps by participants were collected and used for comparisons of driving behaviour in different scenarios. Results concluded that there is no significant difference in the driving behaviour between ***Base*** and ***Mixed*** scenarios at tested MPR. However, in ***DL*** scenario, MV drivers drove closer to their leaders. This was more evident when driving on the middle lane next to the platoons. The MV drivers also accepted shorter gaps in lane changing manoeuvres. In fact, dedicating a lane to CAVs increases the density of CAV platoons on one lane and consequently their conspicuity becomes higher. As a result, MV drivers are influenced by CAV platoons on a DL and imitate their behaviour. This behavioural adaptation should be taken into consideration when evaluating the impacts of DLs on traffic efficiency and traffic safety.

The next research gap that was revealed based on the conceptual framework pertains to the impacts of the presence and utilization policy of a DL on CAV drivers' interactions with the automation system. To fill this research gap, a second driving simulator experiment was conducted including two scenarios: a) ***Mandatory*** scenario: in which the median lane of the motorway was dedicated to CAVs and automation was only allowed on this lane; b) ***Optional*** scenario: in which using the DL was optional, meaning that participants could drive in automated mode on any lane. Under the automated mode participants could adjust the speed and THW and initiate automated lane changes.

CAV drivers' preference to use automation in car-following and lane changing during the experiment runs was assessed. The results revealed that the presence of a DL has no significant impacts on drivers' preference to use automation. However, the DL, especially with mandatory utilization (***Mandatory*** scenario) was found to motivate the drivers to use the median lane (the DL) of the motorway more often. This is a suitable policy for the early stage of implementing DLs for concentrating CAVs on one lane to facilitate platooning.

Additionally, the THWs in car-following and accepted gaps in lane changing between the two driving modes and lane types (i.e., normal vs. dedicated lanes) were compared. The results showed that drivers tend to keep larger THWs and merge into larger gaps when driving in automated mode. However, they perform close car-following on DLs (in automated mode) and accept shorter gaps when changing lane towards the DL, knowing that all vehicles are operating in automated mode. This should be taken into account for more realistic traffic simulations reflecting the impacts of a DL on the behaviour of CAV drivers.

In sum, this thesis firstly, emphasizes the importance of studying the combined effects of traffic safety and efficiency while considering the human driver behaviour and control transitions in both car-following and lane changing in evaluating DLs. Secondly, this thesis provides empirical evidence about the impacts of DLs on the behaviour of human drivers and suggests that DLs increase the chance of keeping smaller THWs in car-following and accepting smaller gaps in lane changing which can contribute to the increase of capacity.

Based on the key findings of this thesis, there are several implications that are relevant to policy-makers, traffic flow modellers, and road designers interested in evaluating the impacts of DLs on traffic performance, taking into account driver behaviour. Firstly, this thesis helps policy makers by providing assessments on possible strategies for implementing DLs for CAVs based on the empirical data collected from the two driving simulator experiments. These strategies entail under which utilization policy the provision of DLs at moderate MPR can offer benefits for all traffic. Secondly, the empirical findings of this thesis, that describe the behaviour of drivers of MVs and CAVs, can be incorporated into existing traffic flow models for evaluating the performance of DLs. This is essential to more realistically evaluate the impacts of automated driving and dedicated lanes. Thirdly, this thesis designed road signs for DLs and investigated the impacts of demarcations and location of such lanes. The insights and conclusions from the empirical data achieved from the driving simulator experiments help infrastructure designers in the design and operation of future roads with DLs.

Building on the work presented in this thesis, several recommendations for directions of future research are formulated. Firstly, it is advised that future studies are carried out with a larger sample of participants that is representative of the driver population. Secondly, due to both technical and ethical reasons, it was not possible to perform a field test, therefore, a virtual reality environment was used to investigate the research questions. This brings along questions regarding real-world impacts of automation and DLs. Besides, driver behaviour was measured over a limited time and at one MPR. So, it would be relevant to test the long-term effects of automation and DLs at different MPRs, conducting field tests in future studies. Thirdly, further research is needed on design, demarcations, and signage of DLs as well as how to educate drivers to inform them about the usage of these lanes. Last but not least, it is recommended to implement the empirical data from the driving simulators to the traffic flow models to evaluate the impacts of automation and DLs on traffic performance.

Samenvatting

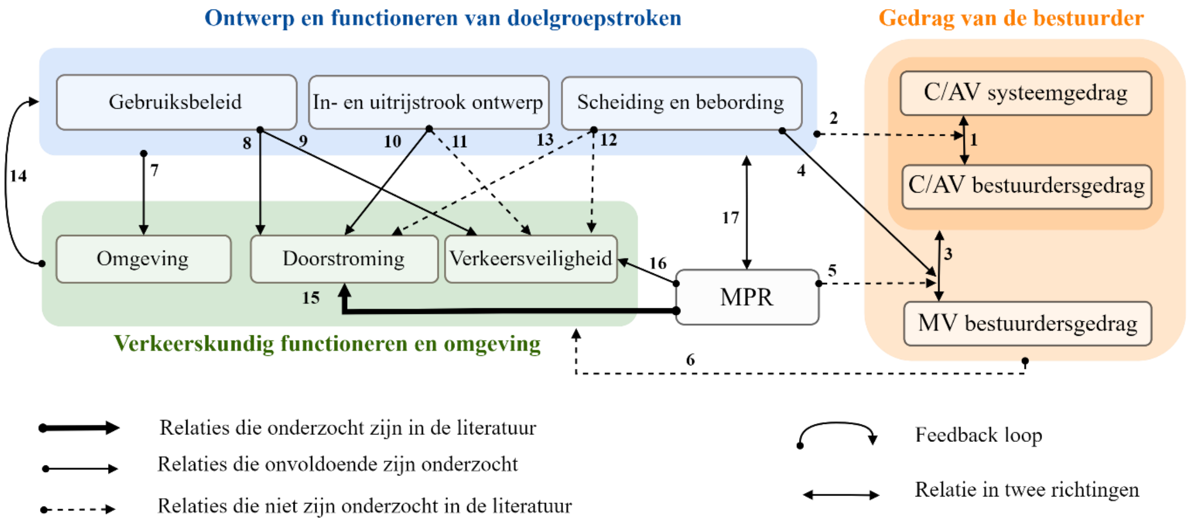
Doelgroepstroken (DL's) zijn voorgesteld als een mogelijk scenario voor bij de uitrol van met elkaar verbonden en geautomatiseerde voertuigen (CAV's) op het wegennet. Kennis over het ontwerp en het functioneren van DL's en hun effecten op het gedrag van bestuurders van CAV's en handmatige voertuigen (MV's) ontbreekt echter in de literatuur. Daarom onderzocht dit proefschrift de volgende twee hoofdvragen:

(1) Wat zijn de onderliggende factoren bij het ontwerp en het functioneren van DL's en wat zijn de relaties tussen deze factoren?

(2) Wat is de impact van een DL op het gedrag van CAV- en MV-bestuurders?

Het beantwoorden van deze twee vragen is van cruciaal belang voor het nemen van beslissingen over het toelaten van CAV's op ons wegennet.

Om bovenstaande vragen te beantwoorden is een aanpak in twee stappen gevolgd. Allereerst is een literatuuronderzoek uitgevoerd om een conceptueel raamwerk te ontwikkelen, dat te zien is in Figuur 1. Het raamwerk bestaat uit de relaties tussen het gedrag van de bestuurder, het ontwerp en het functioneren van DL's en het verkeerskundig functioneren en de omgeving. Dit zijn de drie belangrijkste geïdentificeerde componenten, rekening houdend met de marktpenetratiegraad (MPR) van geautomatiseerde en/of verbonden voertuigen (C/AV's). Het ontwikkelde conceptuele kader identificeert op basis van de literatuur de verbanden die zijn bestudeerd (vetgedrukte pijlen), die te weinig zijn bestudeerd (ononderbroken pijlen) en de verbanden die nog niet aan bod komen in de wetenschappelijke literatuur (onderbroken pijlen). Op basis van het conceptueel kader en de geïdentificeerde kennislacunes wordt een onderzoeksagenda voorgesteld. De onderzoeksagenda benadrukt de noodzaak om de voertuigtypes (d.w.z. de verschillende automatiseringsfuncties) te specificeren die op DL's zijn toegestaan, de noodzaak om de gedragsaanpassing van MV- en C/AV-bestuurders te onderkennen, rekening houdend met de effecten van verschillende MPR's, en het belang van markering en bewegwijzering. Het wordt ook aanbevolen om algoritmen voor het wisselen van rijstrook te ontwikkelen, rekening houdend met connectiviteit tussen C/AV's, die ook kunnen worden geïmplementeerd in rijsimulatoren en verkeerssimulaties. Ten slotte wordt aanbevolen dat toekomstig onderzoek de gecombineerde effecten van verkeersveiligheid het functioneren bij het ontwerpen van DL's onderzoekt, waarbij rekening wordt gehouden met aanpassing van het gedrag van de bestuurder en overgangen tussen handmatige en geautomatiseerde besturing.



Figuur 1 Het conceptuele kader voor de relaties tussen het ontwerp en het functioneren van doelgroepstroken, het gedrag van de bestuurder, de doorstroming en de omgeving.

Het conceptuele kader diende als basis voor de tweede stap, bestaande uit empirische studies om inzicht te krijgen in het gedrag van MV- en CAV-bestuurders in gemengd versus gescheiden verkeer (middels DL's). Een reeks rijsimulatorexperimenten werd gebruikt om observaties van het rijgedrag te verkrijgen.

Het eerste rijsimulatorexperiment was gericht op het onderzoeken van het gedrag van MV-bestuurders in gemengd verkeer op een weg zonder DL, en dat te vergelijken met de situatie waarin MV-bestuurders op een rijstrook naast een DL rijden waar CAV-pelotons rijden. Eenenvijftig deelnemers werd gevraagd om een MV te besturen in een rijsimulator in een vaste opstelling op een 3-strooks snelweg in drie verschillende verkeersscenario's: (1) **Basis**, alleen MV's waren aanwezig in het verkeer, (2) **Gemengd**, pelotons van 2 -3 CAV's reden op alle rijstroken gemengd met MV's, (3) **DL**, pelotons van 2-3 CAV's reden alleen op een DL. De DL was te herkennen aan verkeersborden en een buffermarkering die deze rijstrook scheidde van de overige rijstroken. Voor CAV's werd uitgegaan van een matige penetratiegraad van 43%.

Tijdens de ritten werden de volgtijden van de auto en de door de deelnemers geaccepteerde hiaten verzameld en gebruikt voor vergelijkingen van rijgedrag in verschillende scenario's. Uit de resultaten wordt geconcludeerd dat er geen significant verschil is in het rijgedrag tussen basis- en gemengde scenario's bij geteste MPR. In het DL-scenario reden MV-bestuurders echter dichter bij hun voorgangers. Dit was duidelijker bij het rijden op de middelste rijstrook naast de pelotons. De MV-bestuurders accepteerden ook kortere hiaten bij het wisselen van rijstrook. Door een rijstrook toe te wijzen aan CAV's, neemt de dichtheid van CAV-pelotons op die rijstrook toe, waardoor ze beter opvallen. Hierdoor worden MV-bestuurders beïnvloed door CAV-pelotons op een DL en imiteren hun gedrag. Met deze gedragsaanpassing moet rekening worden gehouden bij het evalueren van de effecten van DL's op doorstroming en verkeersveiligheid.

De volgende onderzoekslacune die aan het licht kwam op basis van het conceptuele kader heeft betrekking op de impact van de aanwezigheid- en gebruiksbeleid van een DL op de interacties van CAV-bestuurders met het automatiseringssysteem. Om deze leemte in het onderzoek te vullen, werd een tweede rijsimulatorexperiment uitgevoerd met twee scenario's: a) **Verplicht** scenario: waarin de linker rijstrook van de snelweg was gereserveerd voor CAV's en geautomatiseerd gebruik alleen op deze rijstrook was toegestaan; b) **Optioneel** scenario: waarin het gebruik van de DL optioneel was, wat betekent dat deelnemers in geautomatiseerde modus op elke rijstrook van de snelweg konden rijden. In de geautomatiseerde modus konden deelnemers de snelheid en volgafstanden aanpassen en automatische rijstrookwisselingen starten.

De voorkeur van CAV-bestuurders om geautomatiseerd te rijden bij het volgen van auto's en het wisselen van rijstrook tijdens de ritten werd beoordeeld. Uit de resultaten bleek dat de aanwezigheid van een DL geen significante invloed heeft op de voorkeur van bestuurders om geautomatiseerd te gaan rijden. Wel bleek de DL, zeker bij verplicht gebruik (scenario Verplicht), de automobilisten te motiveren om vaker de linker rijstrook (de DL) van de snelweg te gebruiken. Dit is een geschikt beleid voor de vroege fase van de implementatie van DL's voor het concentreren van CAV's op één rijstrook om platooning te vergemakkelijken.

Daarnaast werden de volgafstanden en geaccepteerde hiaten in het wisselen van rijstrook tussen de twee rijmodi en rijstrooktypes (d.w.z. normale versus doelgroepstroken) vergeleken. De resultaten toonden aan dat bestuurders de neiging hebben om grotere volgafstanden aan te houden en in grotere hiaten in te voegen wanneer ze in de geautomatiseerde modus rijden. Ze volgen echter auto's van dichtbij op DL's (in geautomatiseerde modus) en accepteren kortere hiaten bij het wisselen van rijstrook richting de DL, wetende dat alle voertuigen op de DL in geautomatiseerde modus werken. Hiermee moet rekening worden gehouden bij meer realistische verkeerssimulaties die de impact van een DL op het gedrag van CAV-bestuurders weerspiegelen.

Samenvattend benadrukt dit proefschrift ten eerste het belang van het bestuderen van de gecombineerde effecten van verkeersveiligheid en doorstroming, terwijl rekening wordt gehouden met het gedrag van de menselijke bestuurder en besturingsovergangen bij zowel het volgen van auto's als het wisselen van rijstrook bij het evalueren van DL's. Ten tweede levert dit proefschrift empirisch bewijs over de impact van DL's op het gedrag van menselijke bestuurders en suggereert het dat DL's de kans vergroten om kleinere volgafstenden aan te houden en kleinere hiaten bij het wisselen van rijstrook te accepteren, wat kan bijdragen aan de toename van de capaciteit van de snelweg.

Op basis van de belangrijkste bevindingen van dit proefschrift zijn er verschillende implicaties die relevant zijn voor beleidsmakers, verkeersmodelleurs en wegontwerpers die geïnteresseerd zijn in het evalueren van de impact van DL's op verkeersprestaties, rekening houdend met het rijgedrag. Ten eerste helpt dit proefschrift beleidsmakers door beoordelingen te geven van mogelijke strategieën voor het implementeren van DL's voor CAV's op basis van de empirische gegevens die zijn verzameld uit de twee rijsimulatorexperimenten. Deze strategieën beschouwen onder welk gebruiksbeleid het aanbieden van DL's tegen een matige MPR voordelen kan bieden voor al het verkeer. Ten tweede kunnen de empirische bevindingen van dit proefschrift, die het gedrag van bestuurders van MV's en CAV's beschrijven, worden opgenomen in bestaande verkeersmodellen voor het evalueren van de prestaties van DL's. Dit is essentieel om de impact van geautomatiseerd rijden en doelgroepstroken realistischer te kunnen beoordelen. Ten derde ontwierp dit proefschrift verkeersborden voor DL's en onderzocht de impact van markering en de locatie van dergelijke rijstroken. De inzichten en conclusies uit de empirische gegevens van de rijsimulatorexperimenten helpen infrastructuurontwerpers bij het ontwerp en de exploitatie van toekomstige wegen met DL's.

Voortbouwend op het werk dat in dit proefschrift wordt gepresenteerd, worden verschillende aanbevelingen voor toekomstig onderzoek geformuleerd. Ten eerste is het raadzaam toekomstige studies uit te voeren met een grotere steekproef van deelnemers die representatief is voor de bestuurderspopulatie. Ten tweede was het om zowel technische als ethische redenen niet mogelijk om een veldtest uit te voeren, daarom werd een virtual reality-omgeving gebruikt om de onderzoeksvragen te onderzoeken. Dit brengt vragen met zich mee over de real-world impact van automatisering en DL's. Daarnaast is het rijgedrag gedurende een beperkte tijd en bij één MPR gemeten. Het zou dus relevant zijn om de langetermijneffecten van automatisering en DL's bij verschillende MPR's te testen, door veldtesten uit te voeren in toekomstige studies. Ten derde is verder onderzoek nodig naar het ontwerp, de markering en de bewegwijzering van DL's, evenals hoe bestuurders kunnen worden opgeleid om hen te informeren over het gebruik van deze doelgroepstroken. Last but not least wordt aanbevolen om de empirische gegevens uit de rijsimulatoren te implementeren in de verkeersmodellen om de impact van automatisering en DL's op de verkeersprestaties te evalueren.

About the Author

Solmaz Razmi Rad was born in 1986 in Tehran, Iran. In 2009, she obtained her Bachelor degree in Civil Engineering at Azad University, Iran. After her graduation, she continued her study in Highway and Transportation and started research on the topics of road safety and driver behaviour at University of Putra, Malaysia. Her Master thesis was titled “Gap Acceptance at un-signalized T-junctions”. She obtained her master’s degree in 2013.

After her Master study, she served as a lecturer in Malaysian University of Science and Technology and Azad university of Tehran, Iran for two years.

In 2017, she joined the Transport & Planning Department of Delft University of Technology, as a researcher, investigating pedestrians’ crossing behaviour in front of CAVs. During this time, she assessed the effectiveness of a communication way between pedestrians and CAVs for a better vehicle intent recognition and safe interaction through agent-based modelling simulation to provide a guide for policymakers.

In June 2018, she continued her research on “Design and Evaluation of Dedicated Lanes for Connected and Automated Vehicles” at the same department, as a Doctoral candidate. During her doctoral studies, she assisted in teaching activities at Delft University of Technology and Beijing Jiaotong University, China. She also served as a reviewer for various international journals and conferences.

She works now as an advisor at RDW (the Dutch Vehicle Authority), developing new knowledge in the field of human factors and vehicle automation and applying it to regulations and implementation to ensure safer automated driving.

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