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### A conceptual framework and research agenda

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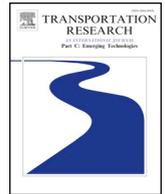
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# Transportation Research Part C

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



Solmaz Razmi Rad<sup>a,\*</sup>, Haneen Farah<sup>a</sup>, Henk Taale<sup>a,b</sup>, Bart van Arem<sup>a</sup>, Serge P. Hoogendoorn<sup>a</sup>

<sup>a</sup> Delft University of Technology, Department Transport & Planning, Delft, The Netherlands

<sup>b</sup> Rijkswaterstaat Water, Traffic and Environment, Rijswijk, the Netherlands

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### ABSTRACT

Dedicated Lanes (DLs) have been proposed as a potential scenario for the deployment of Automated and/or Connected Vehicles (C/AVs) on the road network. However, evidence-based knowledge regarding the impacts of different design configurations, utilization policies, and the design of their access/egress on traffic safety and efficiency is limited. In order to develop an adequate design for DLs, first, a conceptual framework describing the relations and interrelations between these factors and traffic safety and efficiency is needed. Therefore, the main aim of this paper is to develop a conceptual framework accounting for the factors that could affect the safety and efficiency of DLs. This conceptual framework is underpinned based on relevant literature on how the deployment of C/AVs, driver behaviour, and DL design and operation affect traffic safety and efficiency. Based on the conceptual framework, the knowledge gaps on DL design for C/AVs were identified and a research agenda, including prioritization of the research needs, is proposed.

Following the developed conceptual framework, the necessary building blocks for investigating the impacts of different design configurations, utilization policies, and the design of their access/egress on traffic safety and efficiency are: (1) to specify the types of vehicles with certain capabilities allowed to drive on DLs; (2) to incorporate existing algorithms of C/AVs, which reflect more realistically their behaviour, in both driving simulator experiments and microscopic simulation; (3) to translate the empirical data regarding human behavioural adaptation collected from field tests and driving simulator studies to mathematical models and implement them in traffic flow simulation platform. 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.

\* Corresponding author.

E-mail addresses: [S.RazmiRad@tudelft.nl](mailto:S.RazmiRad@tudelft.nl) (S. Razmi Rad), [h.farah@tudelft.nl](mailto:h.farah@tudelft.nl) (H. Farah), [H.Taale@tudelft.nl](mailto:H.Taale@tudelft.nl) (H. Taale), [B.vanArem@tudelft.nl](mailto:B.vanArem@tudelft.nl) (B. van Arem), [S.P.Hoogendoorn@tudelft.nl](mailto:S.P.Hoogendoorn@tudelft.nl) (S.P. Hoogendoorn).

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## 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 et al., 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, 2015). 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, Wiedemann, Stevens, Brunett & Reed (2014) and Yang, Farah, Schoenmakers & Alkim (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 et al., 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 et al., 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 the scope of the study is presented followed by the conceptual framework which is presented in Section 3. Section 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 5 identifies the knowledge gaps and proposes a research agenda based on the reviewed literature. Finally, Section 6 describes the main conclusions of the paper.

### 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 et al., 2016a), fairness, pricing (Litman, 2015) and impacts of implementing DLs across the transportation network (Chen et al., 2017a,b) are of concern when these lanes are implemented, they are not within the scope of this study.

### 3. Conceptual framework

Starting from the notion that road design influences driver behaviour (Ariën et al., 2017; Baas and Charlton, 2005; Martens et al., 1997) and impacts traffic safety and efficiency (Wang et al., 2013), a conceptual framework is derived, as illustrated in Fig. 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.

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 et al., 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.

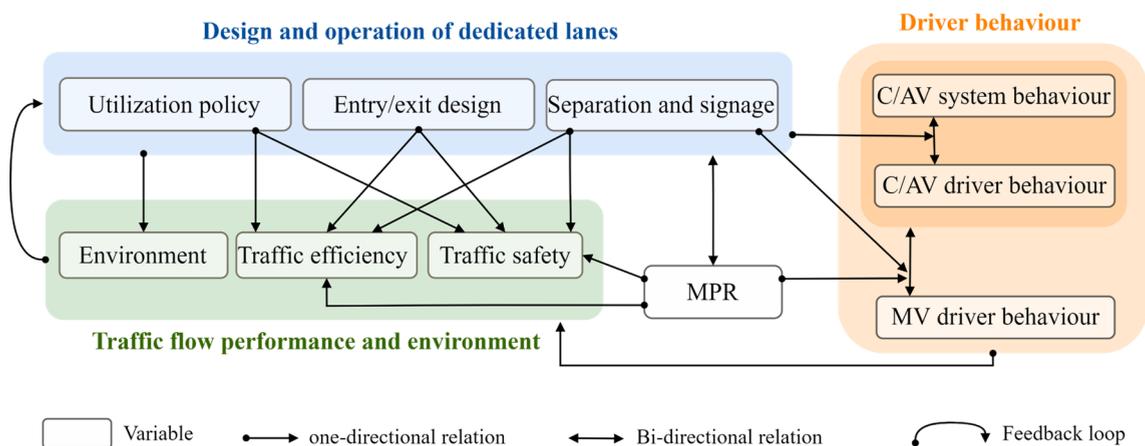


Fig. 1. Conceptual framework for the relations between the design and operation of dedicated lanes, driver behaviour, traffic flow performance and the environment.

**Table 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

#### 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 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.

##### 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](#).

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 3](#). As it is reported in [Table 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 et al., 2006](#); [Fakharian Qom et al., 2016](#); [Ivanchev et al., 2017](#); [Xiao et al., 2019](#); [Amirgholy et al., 2018](#); [Vander Laan and Sadabadi, 2017](#); [Ye and 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

**Table 2**  
Limited entry/exit configurations suggested by literature.

Authors	Specifications	Impacts found
Tsao et al. (1993)	<ul style="list-style-type: none"> <li>- Segregated Highway (without mixing automated traffic with manual traffic) with CAVs</li> <li>- Segregated Highway with AVs</li> <li>- Shared Highway (with dedicated lanes) with Barriers and CAVs</li> <li>- Shared Highway with Barriers and AVs</li> <li>- Shared Highway without Barriers and with CAVs</li> <li>- Shared Highway without Barriers and with AVs</li> </ul>	No impact assessment was conducted
Varaiya (1995)	<ul style="list-style-type: none"> <li>- 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.</li> <li>- Two left most lanes are DLs with no designated entry/exit. Dedicated elevated ramps provide access to the second most left lane. At least 5 km not elevated section of road exists between on and off-ramps. The two right lanes are manual lanes</li> <li>- Two left most lanes are DLs. Dedicated elevated ramps provide access to both DLs. At least 5 km not elevated section of road exists between on and off-ramps. The two right lanes are manual lanes</li> <li>- The leftmost lane is DL consisting of an at least 2 km 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.</li> </ul>	No impact assessment was conducted
Ioannou (1997)	<ul style="list-style-type: none"> <li>- At-grade (lane conversion): one lane is converted to DL</li> <li>- At-grade (median): Available space within the median is used for C/AV lanes</li> <li>- 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</li> <li>- 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</li> <li>- Above-grade (median): Available space within the median is used for the structure supporting the elevated C/AV lane</li> <li>- Above-grade (shoulders): available space beyond the outside shoulders is used for the structure supporting the elevated C/AV lane</li> <li>- Below-grade (tunnel): A C/AV lane constructed below the existing grade level of the freeway</li> </ul>	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

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 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 2.4 s, those for a CAV following an MV from 0.5 to 2.6 s, those for an MV following a CAV from 0.6 to 2.6 s, and those between two CAVs from 0.3 to 2.0 s. 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.

#### 4.1.1.1. 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.

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

**Table 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)	<ul style="list-style-type: none"> <li>- MIXIC traffic simulation</li> <li>- Intra-string THW: 0.5 s</li> <li>- Inter-string THW: 1.4 s</li> <li>- CACC, No lateral automation</li> <li>- Penetration rates in steps of 20% (0% – 100%)</li> </ul>	Four-lane motorway with a lane drop, with DL in some scenarios	<ul style="list-style-type: none"> <li>- At MPRs &lt; 40%, the DL leads to a degradation of performance (lower speeds, higher speed variances, and more shockwaves).</li> <li>- At MPRs &gt; 60% the DL could improve traffic stability by lower speed variances, but only for the high-volume stretch before the bottleneck</li> </ul>
Ivanchev et al. (2017)	<ul style="list-style-type: none"> <li>- Agent-based macroscopic simulation</li> <li>- THW: 0.5 s, 1 s</li> <li>- No connectivity for AVs</li> </ul>	The whole road network of the city of Singapore in morning commute hours	<ul style="list-style-type: none"> <li>- Travel time of MVs increases significantly at MPRs ranging 40–50%.</li> <li>- Roads leading to the highways exhibit higher demand and congestion since more AVs use the highways to reach the DLs</li> </ul>
Vander Laan and Sadabadi (2017)	<ul style="list-style-type: none"> <li>- Adopted Newell (2002) linear car-following to model AVs, applied in CORridor MACro simulation software</li> <li>- Three scenarios were compared using THWs 0.7 s, 0.5 s, and 0.3 s</li> <li>- No connectivity for AVs</li> <li>- Merging and friction effects were ignored</li> </ul>	Four-lane highway with one DL was simulated from 4:00–6:00 PM on weekdays	<ul style="list-style-type: none"> <li>- Best performance is seen at MPRs 30%, 40%, and 50% for THWs 0.7 s, 0.5 s, and 0.3 s respectively. Afterwards, the traffic degrades significantly.</li> </ul>
Liu et al. (2018b)	<ul style="list-style-type: none"> <li>- CACC modelling framework was developed based on the NGSIM oversaturated flow human driver model (Yeo et al., 2008)</li> <li>- CACC car following model derived from the field CACC tests (Milanés and Shladover, 2014)</li> <li>- Vehicle dispatching model assigned the CACC vehicles to DLs, or the adjacent lane if DL was at capacity</li> <li>- Introduced anticipatory lane changing</li> <li>- MVs were equipped with Vehicle Awareness Devices (VAD)</li> <li>- THW of CACC vehicles: 0.6 s (57%), 0.7 s (24%), 0.9 s 7%, and 1.1 s (12%).</li> </ul>	Two networks were tested: a) four-lane freeway segment of 7 km long with an on- and an off-ramp; b) four-lane freeway segment of 18-km long with complex on and off-ramps and weaving bottlenecks	<ul style="list-style-type: none"> <li>- DL and VAD strategies significantly improved the pipeline capacity (8–23%).</li> <li>- The DL strategy performs slightly better than the VAD strategy.</li> <li>- 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.</li> <li>- Both strategies increased the bottleneck capacity while VAD performed better than DL.</li> </ul>
Rahman and Abdel-Aty (2018)	<ul style="list-style-type: none"> <li>- VISSIM microscopic simulation</li> <li>- THW for CAVs: 0.6 s</li> <li>- Car following models used: <ul style="list-style-type: none"> <li>o MVs: Wiedemann 99</li> <li>o CAVs: IDM along with three platoon joining schemes: rear, front, and cut-in joins</li> </ul> </li> </ul>	A congested expressway with 17 weaving segments with one DL MPR: 40%	<ul style="list-style-type: none"> <li>- 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</li> <li>- 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.</li> <li>- DLs outperformed the other two scenarios with improved longitudinal safety.</li> </ul>
Xiao et al. (2019)	<ul style="list-style-type: none"> <li>- Microscopic traffic simulator, MOTUS</li> <li>- CACC vehicles</li> <li>- Intra-string THW: 0.6 s-1.1 s</li> <li>- Inter-string THW: 1.5 s</li> <li>- Lane change was modelled according to LMRS (Schakel et al., 2013)</li> </ul>	3–5 lane Highway with one HOV lane converted to DL with continuous access, operating in the morning peak (06:00–10:00 AM)	<ul style="list-style-type: none"> <li>- At MPRs (%): <ul style="list-style-type: none"> <li>o 10–20: congestion and travel time of the whole vehicle fleet increased</li> <li>o 30: congestion and travel time was comparable to the reference case (the leftmost lane is HOV lane)</li> <li>o 40–50: congestion and travel time reduced</li> </ul> </li> <li>- Speed reduction was observed at bottlenecks due to the friction effect</li> </ul>

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 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.

**Table 4**  
Summary of literature comparing different access types of DLs.

Authors	DL configurations	Method/AV specifications	Impacts found
Zhong (2018)	<ul style="list-style-type: none"> <li>- Dedicated lane to CAVs with continuous access (DL);</li> <li>- DL with limited access (DLA).</li> </ul>	<ul style="list-style-type: none"> <li>- Multi-objective optimization control algorithm;</li> <li>- Objectives for a CACC platoon:               <ul style="list-style-type: none"> <li>o mobility</li> <li>o comfortability</li> <li>o emission</li> <li>o fuel consumption</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>- 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%;</li> <li>- 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);</li> <li>- The highest percentage for platooned CACC is 51% at 50% MPR on DLA. While DL decreased platooning probability at all tested MPRs.</li> </ul>
Yang et al. (2019)	<ul style="list-style-type: none"> <li>- DL with a) continuous and b) limited access</li> <li>- Weaving section length: a) 600 m, b) 800 m, and 1000 m</li> </ul>	<ul style="list-style-type: none"> <li>- VISSIM microscopic simulation</li> <li>- THW: 0.5 s</li> <li>- Platoon size: 2–5 CAVs</li> </ul>	<ul style="list-style-type: none"> <li>- Access type: Traffic flow increased that of baseline from MPR = 15–20% for continuous access and MPR = 30–35% for limited access</li> <li>- Weaving section length: caused no significant change in traffic flow.</li> </ul>

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).

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 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 m after the on-ramp and starts 1000 m 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

**Table 5**  
Summary of literature regarding access types of HOV lanes.

Authors	Lane configurations	Impacts Found
Hearne (1998)	<ul style="list-style-type: none"> <li>- Investigated accident statistics on barrier separated HOV lanes in the years of 1994 and 1995</li> </ul>	<ul style="list-style-type: none"> <li>- 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.</li> </ul>
Jang et al. (2009)	<ul style="list-style-type: none"> <li>Collision data from the Traffic Accident Surveillance and Analysis System for two types of HOV facilities were examined:               <ul style="list-style-type: none"> <li>- continuous access</li> <li>- limited access, considering: a) shoulder width, b) length of the access, and c) proximity of the access to nearest ramps</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>- Higher shoulder widths decrease accidents.</li> <li>- The limited access exhibited a higher collision rate.</li> <li>- Entry/exits with short access length (~402 m) which were located near to on- or off-ramps (within ~ 483 m) had significantly higher accident rates.</li> </ul>
Jang et al. (2013)	<ul style="list-style-type: none"> <li>- Four types of HOV operations were evaluated:               <ul style="list-style-type: none"> <li>o part-time continuous access</li> <li>o full-time limited access with buffer separation</li> <li>o full-time continuous access</li> <li>o part-time limited access with buffer separation.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>- Continuous access HOV lanes lead to higher speed differences when normal lanes are congested</li> <li>- Vehicle-mile-travelled on both configurations are comparable. However, limited access has wider variations</li> <li>- Limited access separates the traffic safely with preventing too many lane changes as well as last-second traffic weaving manoeuvres for lane changing</li> </ul>

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.

#### 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 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., 201a,b; Zhong, 2018; Ong et al., 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. (2016a,b) 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.

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.

#### 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 to 14 feet (~0.6–4.3 m); (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 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).

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 Fig. 2.

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.

**Table 6**  
Summary of literature regarding utilization policies of dedicated lanes.

Authors	DL utilization policy	Method/AV specifications	Impacts found
Chen et al. (2017a,b)	<ul style="list-style-type: none"> <li>- (A, R) left lane only allows CAV platoons, right lane only allows MVs;</li> <li>- (M, R) left lane allows mixed traffic, right lane allows MVs only;</li> <li>- (A, M) left lane only allows CAV platoons, right lane allows mixed traffic</li> </ul>	<ul style="list-style-type: none"> <li>- Analytical study</li> <li>- MPRs: 0–100%</li> </ul>	<ul style="list-style-type: none"> <li>- (A, R): leads to lower capacity until the penetration rate at which both lanes reach their respective physical lane capacities<sup>1</sup> (<math>P_{crit}</math>)</li> <li>- (M, R): Suitable policy for <math>MPR &lt; P_{crit}</math></li> <li>- (A, M): Suitable policy for <math>MPR &gt; P_{crit}</math></li> </ul>
Talebpour et al. (2017)	<ul style="list-style-type: none"> <li>- AVs must go to the DL and they can operate automated everywhere (<b>forced everywhere</b>);</li> <li>- AVs must go to the DLs but must operate manually in normal lanes (<b>forced reserved</b>);</li> <li>- AVs can use the DL and they can operate automated everywhere (<b>optional everywhere</b>).</li> </ul>	<ul style="list-style-type: none"> <li>- Microscopic simulation study</li> <li>- MPRs: 0%, to 30% in steps of 10%</li> </ul>	<ul style="list-style-type: none"> <li>- <b>Forced everywhere</b>: increased the congestion and scatter in the fundamental diagram and caused shockwave formation due to the mandatory lane changes towards DLs</li> <li>- <b>Forced reserved</b>: Increased congestion and shockwaves but decreased average travel time</li> <li>- <b>Optional everywhere</b>: 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.</li> </ul>
Zhong (2018)	<ul style="list-style-type: none"> <li>- All vehicles can drive on all lanes (UML)</li> <li>- One lane is allocated to HOVs and CAVs (MML)</li> <li>- One dedicated lane to CAVs with continuous access (DL)</li> <li>- DL with limited access (DLA).</li> </ul>	<ul style="list-style-type: none"> <li>- Multi-objective Optimization control algorithm</li> <li>- MPRs: 0% (baseline) to 50% in steps of 10%</li> </ul>	<ul style="list-style-type: none"> <li>- <b>UML</b>: network travel time, throughput, and travel time reliability improved at all tested MPRs compared to all other strategies.</li> <li>- <b>MML</b>: 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 <math>MPRs &lt; 25\%</math>.</li> <li>- <b>DLA</b>: 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 <math>MPR = 40\%</math>. Travel time for CACC vehicles decreased drastically. The best strategy for platooning probability at <math>MPR = 25\%</math>.</li> <li>- <b>DL</b>: Always fell behind other strategies except for travel time of CACC vehicles. Only outperformed DLA at network throughput when <math>MPR = 45\%</math>. Reduced platooning probability at all tested MPRs.</li> </ul>
Ong et al. (2019)	<ul style="list-style-type: none"> <li>- 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</li> <li>- DL was separated via double solid lane marking and limited access was allowed on designated dashed lane striping</li> </ul>	<ul style="list-style-type: none"> <li>- Microscopic simulation study</li> <li>- MPRs: 10%, 25%, 35%, and 45%</li> </ul>	<ul style="list-style-type: none"> <li>- At low MPRs, sharing CACC vehicles with HOVs prevented congestion on normal lanes.</li> <li>- The highest increase of throughput compared to the baseline happened at 35% CACC with 1 DL</li> </ul>
Mohajerpoor and Ramezani (2019)	<p>Four lane use policies were defined in a two-lane per direction motorway:</p> <ul style="list-style-type: none"> <li>- Policy A: one lane is dedicated to CAVs and one lane to MVs</li> <li>- Policy B: CAVs and MVs could use both lanes</li> <li>- Policy C: one lane is dedicated to CAVs and the other lane could be used by both</li> <li>- Policy D: one lane is dedicated to MVs and the other lane could be used by both</li> </ul>	<ul style="list-style-type: none"> <li>- Analytical study</li> <li>- MPRs: 0–100%</li> </ul>	<ul style="list-style-type: none"> <li>- 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: <ul style="list-style-type: none"> <li>o Policy D for <math>0\% \leq EPR \leq 50\%</math></li> <li>o Policy A for <math>&lt; 50\% EPR &lt; 65\%</math></li> <li>o Policy C for <math>65\% \leq EPR \leq 100\%</math></li> <li>o Above all, policy B returns near optimal delays for all the EPR ranges</li> </ul> </li> </ul>

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

#### 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.

**Table 7**

Summary of literature regarding the separation of managed lanes.

Authors	Separation	Tools/scenario description	Impacts found
Awan et al. (2018)	<ul style="list-style-type: none"> <li>- Hard separation with tubular delineators and vegetation or grass strip</li> <li>- Soft separation with solid double line and cross hatch marking</li> </ul>	<b>Driving simulator:</b> 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)	<ul style="list-style-type: none"> <li>- Hard separation with guardrails</li> <li>- Soft separation with buffer</li> </ul>	<b>Driving simulator:</b> 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

**Fig. 2.** Examples of hard and soft separation on managed lanes used in the literature.

#### 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 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.

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 9). Hoedemaeker and Brookhuis (1998) conducted a driving simulator study and found that AV drivers adapt their behaviour when

**Table 8**  
Summary of literature in behavioural adaptation of MV drivers.

Authors	Tools and scenario description	Impacts Found
(Gouy et al., 2013)	<b>Driving simulator:</b> Participants followed a lead vehicle in the following scenarios: <ul style="list-style-type: none"> <li>- Baseline scenario with no CAV</li> <li>- Platoons of 20 CAVs were present with THW = 0.3 s</li> <li>- Platoons of 20 CAVs were present with THW = 1 s</li> </ul>	<ul style="list-style-type: none"> <li>- No change in preferred THW of participants</li> <li>- The mean THW was higher in baseline</li> <li>- Only a small difference in THW kept by participants when driving next to platoons keeping THW of 0.3 s compared to 1 s</li> <li>- In platoon conditions and especially in THW0.3 s drivers were very close in average to the limit of preferred THW.</li> </ul>
(Gouy et al., 2014)	<b>Driving simulator:</b> Participants followed a lead vehicle in the following scenarios: <ul style="list-style-type: none"> <li>- Baseline scenario with no CAV</li> <li>- Platoons of 10 trucks were present with THW = 0.3 s</li> <li>- Platoons of 4 trucks were present with THW = 1.4 s</li> </ul>	<ul style="list-style-type: none"> <li>- Participants maintained on average a smaller THW in scenario 2 than in scenario 3.</li> <li>- No significant difference due to the THW order (short-large vs large short)</li> <li>- The mean of minimum THWs was smaller in scenario 2 than in scenario 3</li> <li>- The standard deviation of lateral position was shorter in than THW1.4 s</li> </ul>
Yang et al. (2019)	<b>Driving simulator:</b> Participants followed a lead vehicle in the following scenarios: <ul style="list-style-type: none"> <li>- Baseline scenario with no CAV</li> <li>- CAV platoons were present with THW = 0.5 s mixed with MVs</li> <li>- CAV platoons were present with THW of 0.5 s on DLs with:               <ul style="list-style-type: none"> <li>o continuous access,</li> <li>o limited access with buffer</li> <li>o limited access with barrier</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>- Scenario 3(c) could have a positive impact on behavioural adaptation of MV drivers</li> </ul>

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?

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 and 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

**Table 9**  
Summary of literature in behavioural adaptation of C/AV drivers.

Authors	Tools and scenario description	Impacts found
Hoedemaeker & Brookhuis (1998)	<b>Driving simulator:</b> 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 = 1 s, THW = 1.5 s - ACC was not over-rulable with preferred THW, THW = 1 s, THW = 1.5 s	a) all groups chose higher speed when driving with ACC b) The SDLP 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)	<b>Field operational test:</b> 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)	<b>Field operational test:</b> 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 0.5 s 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)	<b>Driving simulator:</b> 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 ACCd) behavioural adaptation did not lead to unsafe driving
Skottke et al. (2014)	<b>Driving simulator:</b> The first group of drivers performed three sections of driving: o pre-automation (manual drive), o automation (ACC, THW = 0.3 s 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 and Boyle (2019)	<b>Driving simulator:</b> 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.

role of driver's characteristics on this phenomenon is not fully studied for C/AV drivers and is lagged behind for MV drivers.

#### 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)).

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 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, Beggiano & Petzoldt (2015) showed that drivers are more likely to switch to manual mode in situations that are impossible to handle

**Table 10**  
Summary of literature in driver-initiated driver in control transitions.

Authors	Tools and scenario description	Impacts found
Viti et al. (2008)	<b>Field operational test:</b> - 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)	<b>Field operational test:</b> 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)	<b>Field operational test:</b> 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

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 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

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

Authors	Tools and scenario description	Impacts found
Varotto et al. (2015)	<b>Driving simulator study:</b> 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 and Stanton (2017)	<b>Driving simulator study:</b> 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 from automated mode was calculated as: o $4.46 \pm 1.63$ s when not engaged in a secondary task o $6.06 \pm 2.39$ 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.

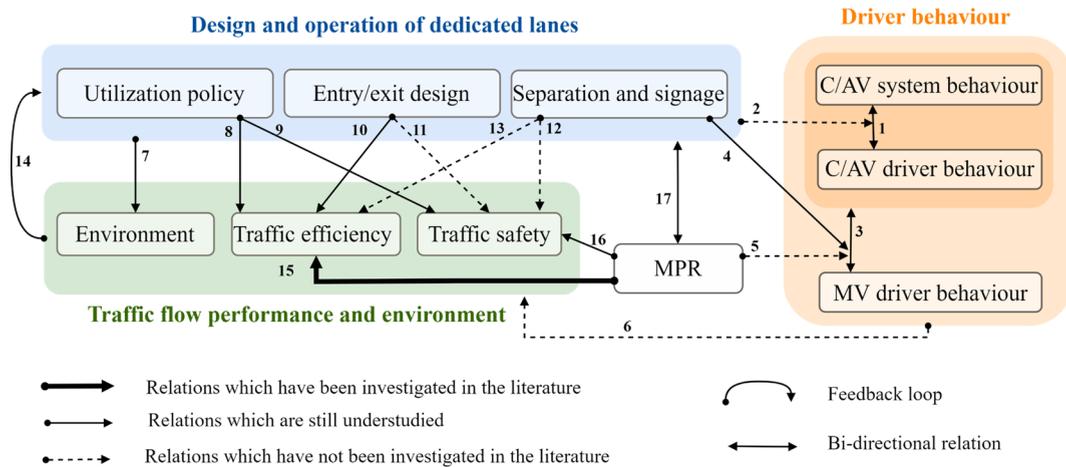


Fig. 3. Conceptual framework for the relations between the design and operation of dedicated lanes, driver behaviour, traffic flow performance and the environment.

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.

### 5. Research agenda

Based on the review and the identified research gaps in the literature, the conceptual framework is presented again in Fig. 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 Fig. 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.

#### 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).

## 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**)?

## 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 (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.

### 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, 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.

### 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.

## 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.

### CRedit authorship contribution statement

**Solmaz Razmi Rad:** Conceptualization, Methodology, Investigation, Writing - original draft. **Haneen Farah:** Methodology, Supervision, Writing - review & editing, Funding acquisition, Project administration. **Henk Taale:** Methodology, Supervision, Writing - review & editing, Funding acquisition. **Bart Arem:** Supervision. **Serge P. Hoogendoorn:** Supervision.

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