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The impact of the presence and utilization policy of a dedicated lane on drivers' preference to use automation and driving behaviour on motorways

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ABSTRACT

Dedicated Lanes (DLs) have been proposed as a potential alternative for the deployment of Connected and Automated Vehicles (CAVs) to facilitate platooning and increase motorway capacity. However, the impact of the presence and utilization policy of such a lane on drivers' preference to use automation and their behaviour has not yet been thoroughly investigated.

In this study, a driving simulator experiment is conducted, where participants drive a CAV in the presence of a DL with different utilization policies. Drivers have the possibility to choose between driving in an automated mode or in a manual mode. In automated mode they could adjust the driving speed and time headway and initiate automated lane changes. Two utilization policies were examined: mandatory versus optional use of DLs when driving in an automated mode. The impact of the presence and utilization policy of the DL on drivers' preference to use automation and their behaviour in car-following and lane changing are investigated.

The study found that while the presence of a DL does not increase drivers' preference for automation use, it encourages drivers to utilize the DL more when the utilization policy is mandatory (i.e., drivers can only use automation mode when driving on this lane). Furthermore, drivers are more conservative in automated mode and when driving in mixed traffic. However, they perform closer car-following and merge into smaller gaps when driving on DLs which on one hand can increase the capacity of the DLs, but on the other hand can increase the risk of collisions. These results are useful for road operators, and in setting-up a more realistically traffic simulation studies.

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 short

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THWs in the range of 0.3 to 1.1 s (Vander Laan and Sadabadi, 2017; Liu et al., 2018). However, mass adoption of small THWs as assumed for platooning in these studies depends on the users' acceptance, trust, and preferences (Sarker et al., 2020).

According to the literature, individuals tend to exhibit different risk-taking behaviours and preferences for THW settings when driving an automated vehicle. For instance, Horswill and McKenna (1999), have shown that when individuals relinquish control of driving to automated systems, they tend to take lower risks and possibly choose larger THWs. Similarly, research by Basu et al. (2017) indicates that drivers demonstrate a preference for a more defensive driving style in an automated vehicle compared to their own driving style. In their study, participants were asked to drive in a driving simulator in a manual and in a fully automated modes on two different days. A significant difference was found between how the participants drove in a manual mode, and how they preferred to be driven in an automated mode, which was in a more defensive driving style.

In studying THW preferences further, Kessler et al. (2012) asked participants to drive a vehicle equipped with ACC and forward collision warning for a duration of 12 months. They reported an increase in the size of THW when using an Adaptive Cruise Control (ACC). Additional investigations by Bianchi Piccinini et al. (2014) in a driving simulator setting and Schakel et al. (2017) in a naturalistic driving study further explored THW preferences with ACC. In line with Kessler et al. (2012), they found larger THW adoption among participants using ACC. On the contrary, Nowakowski et al. (2011) conducted a field study observing drivers' choices of THW settings in automated driving. According to the results, the shortest THW settings available by the ACC and Cooperative ACC (CACC) equipped vehicles were chosen most frequently by the participating drivers.

The results of these studies imply that human drivers behave differently when driving in an automated mode compared to manual mode. Therefore, the relation between automated driving and THW is not as simple as it seems.

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.

Human drivers behave differently when interacting with automated vehicles compared to manual ones. For example, when interacting with recognizable automated vehicles, drivers tend to perform closer car-following (Rahmati et al., 2019) and merge closer in front of them (Soni et al., 2022). Thus, given that all vehicles on a DL are automated, the behaviour of human drivers might be different on DLs. This prompts consideration of how drivers' behaviour regarding car-following and gap acceptance in lane changing might differ on a DL where all vehicles are automated.

Trust in and acceptance of automation could also have an impact on driver's behaviour. In a driving simulator study by Tomasevic, Young, Horberry, & Fildes, (2022), the factors that may influence drivers' willingness to engage in automation during every day driving were investigated. It was found that drivers were less willing to engage automation in car-following situations (THWs less than 1.5 s in this study) compared to free-flow driving.

Another relevant consideration is the extent to which a DL can influence CAV drivers' preferences to use automation. Different utilization policies, such as mandatory use of DLs when driving in automated mode (automation allowed only on DLs) versus optional use of DLs (i.e., automation allowed on all lanes), could have an impact on traffic performance and traffic safety (He, Ding, Lu, & Qi, 2022; Talebpour, Mahmassani, & Elfar, (2017)). 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 CAV drivers under different utilization policies (Razmi Rad et al., 2020; Sharma et al., 2018).

Driver characteristics can also play a role in driving behaviour and preferences 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 (Kadylak, Cotten, & Fennell, 2021; Nielsen & Haustein, 2018; Piao, McDonald, Henry, Vaa, & Tveit, 2005; Rödel, Stadler, Meschtscherjakov, & Tscheligi, 2014). 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 CAV drivers' preferences to use automation and their behaviour 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) on motorways. Therefore, the research questions investigated in this study are as follows:

1. What is the impact of DL presence on the preference to use automation in car-following and lane change manoeuvres?
2. What is the impact of the driving mode and the presence of a DL on the car-following THW?
3. What is the impact of the driving mode and the presence of a DL on the gap acceptance in lane changing manoeuvres?

It should be noted that, in this paper, CAV refers to connected and automated vehicles. These vehicles are able to drive in platoons keeping short THWs, corresponding to SAE levels 4 and 5 (SAE, 2018), which are capable of connectivity.

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 manoeuvres in manual mode or let the system perform these manoeuvres in an automated mode. Different scenarios with and without dedicated lanes and different utilization policies were considered.

In the remainder of this article, the method is described in section 2 and the results of the driving simulator experiment are presented in section 3. The discussion is presented in section 4, and finally the conclusions and future research directions are presented in section 5.

2. Method

2.1. 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. Three age categories were considered: Young (20–40), Middle age (40–65), and Elderly (65–80). Their age and gender distribution is as follows: 20–40 (5 females, 12 males), 40–65 (7 females, 13 males), 65–80 (1 female, 10 males).

2.2. Apparatus

The study was conducted in a fixed-based driving simulator comprised of a dashboard mock-up with three 4 K 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 Fig. 1. Three different THWs were available to choose from: 0.5 s, 1 s, and 1.5 s. We chose THWs less than 1.5 s because the average THW during capacity conditions on Dutch freeways is approximately 1.5 s, corresponding to a capacity of 2,400 vehicles per hour per lane (Grontmij, 2015). Hence, the THW of 1.5 s represents the range within which participants feel comfortable while interacting with the lead vehicle. Given that the aim of automated vehicles is to enhance capacity, THWs exceeding 1.5 s were deemed not ideal. Consequently, we selected two additional THW values, each differing by 0.5 s. The time headway of 1 s 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. Participants could also see the adjusted time headway icon on the screen as shown in Fig. 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 mode was also dependant on the car-following.

Two more buttons (left side of the steering wheel) were assigned to increase and decrease the desired driving speed by participants as shown in Fig. 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 message would appear on the screen stating, for example: ***"The desired speed is 70 km/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 set to active, the throttle, the brake pedals, and the steering wheel became inactive, while when driving in manual mode, all the automation functionalities were set to 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".***

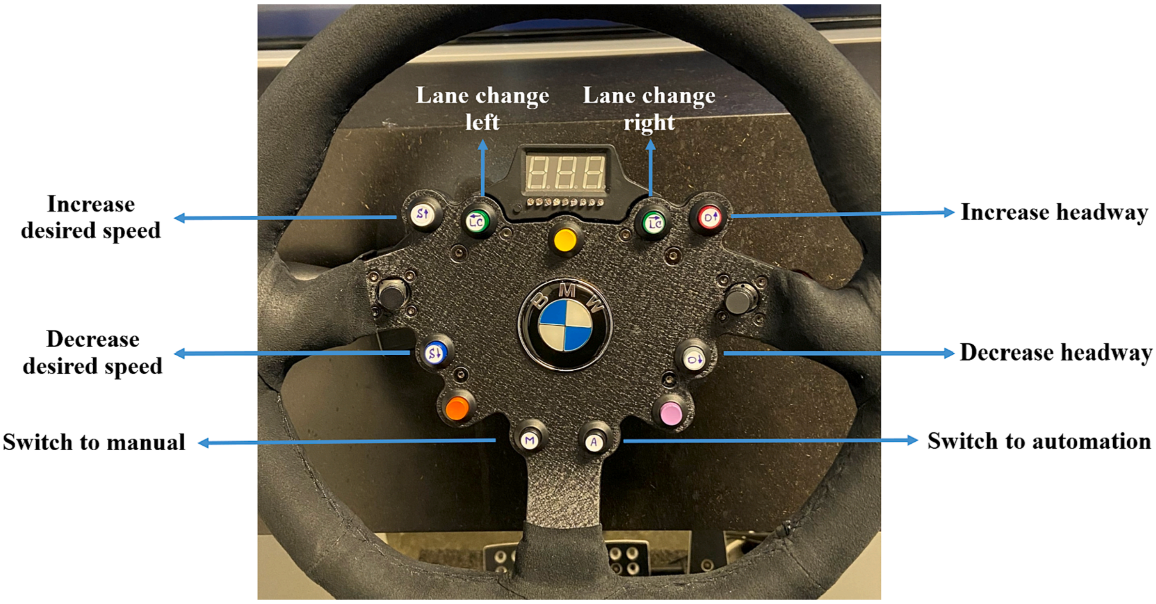


Fig. 1. The steering wheel including the different buttons to adjust the automated driving mode.

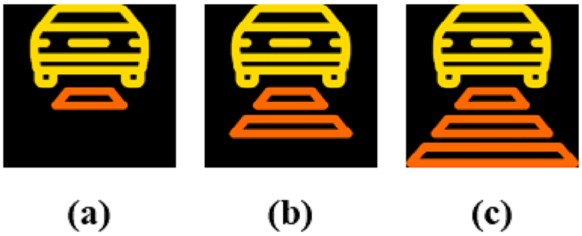


Fig. 2. Time headway icons appearing on the screen, (a) 0.5 s, (b) 1 s, and (c) 1.5 s.

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 min between sessions. Each participant was rewarded with a voucher of €15 for participating in the experiment.

2.4. *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 Fig. 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.

Mandatory scenario (Fig. 3 (a)): In two sections (2 and 4) of the motorway the left most lane (median lane) was dedicated to CAVs. Participants had to drive on the DL when in automated mode and were not allowed to drive on the normal lanes (NLs) unless they 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 penetration rate was 40 %. Intra-platoon and inter-platoon THWs were set to ranges of "0.5 s −1s" and "2s − 4 s", respectively.

To inform the participants about the dedicated lane and to further clarify the purpose of this lane, a buffer demarcation separating the DL from the other lanes was applied together with road signs with a platooning pictogram, following Razmi Rad et al. (2021), as illustrated in Fig. 4.

During *Mandatory* scenario, just before entering segment 3 without a DL (see Fig. 3(a)), the participants were notified, via a text message appearing on the screen stating ***"Please switch to manual mode"***, to continue driving manually. When automation was available at the beginning of segments 2 and 4 with DL, the participants were notified, via a text message ***"automation is available"***,

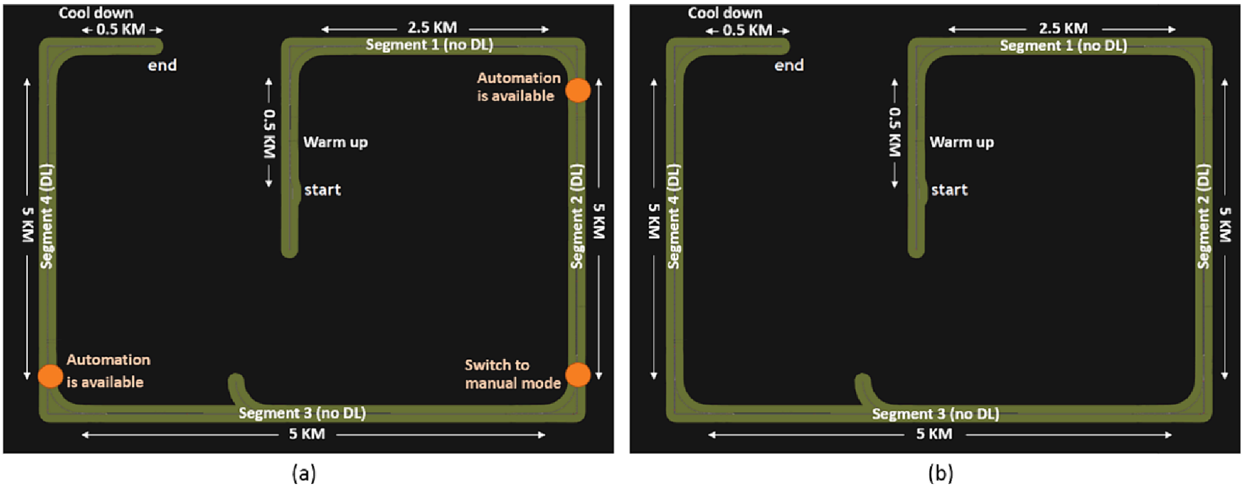


Fig. 3. Top view of the road network, (a) *Mandatory* scenario; (b) *Optional* scenario.

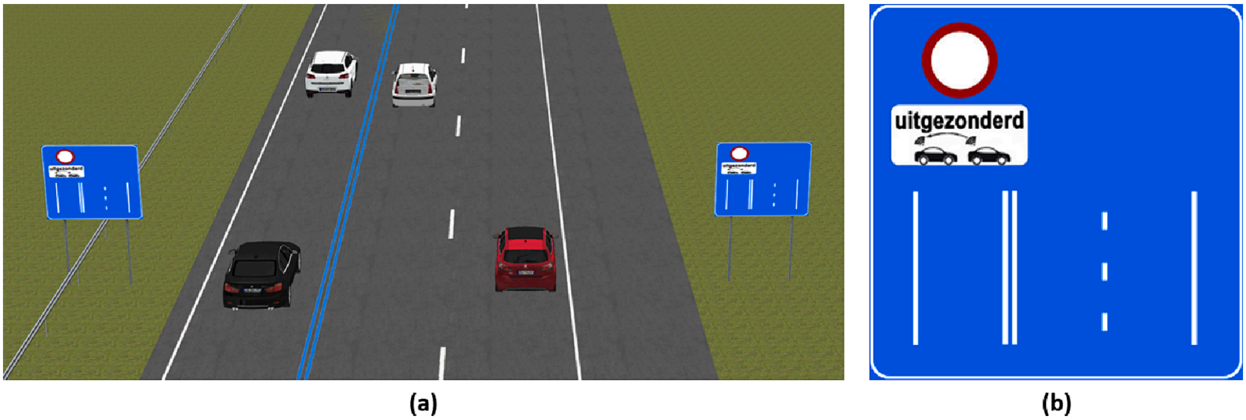


Fig. 4. (a) DL demarcation, (b) Road sign for DL (“uitgezonderd” means “except for” in Dutch).

stating that automation was available and they had the freedom to decide to switch to automated mode and drive on the DL, or continue driving manually on the NLs.

Optional scenario (Fig. 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 DLs. 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.

2.5. *Questionnaires*

The participants were also asked to fill in a set of questionnaires. The first questionnaire aimed to obtain information about the participants’ 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 (i.e., The system is reliable;) 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).

2.6. *Data collection and processing*

During the experiment runs, the driving simulator registered every 0.5 s 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).

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 Fig. 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 3 s (Pasanen & Salmivaara, 1993; Highway Capacity Manual, 2010).
- **Lane changing gap** was calculated as the sum of the headway [m] and lag gap [m] divided by the speed [m/s] of the ego and lag vehicle respectively. A lane change moment was defined as when the front centre of the ego vehicle passes the lane marking (see Fig. 5 (b)). Four lane change manoeuvres were defined as illustrated in Fig. 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 lane changing manoeuvres 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.

Although lane change manoeuvres are commonly categorized as mandatory or discretionary in the literature (Balal et al., 2014), we have further categorized the lane changes based on the reasons behind these manoeuvres. So, mandatory lane changes consist of on- and off-ramp lane changing manoeuvres, while discretionary lane changes consist of overtaking and keep right.

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 75 m. So, a limitation of 75 m for the longitudinal distance for lane change gaps was considered for both THW and lag gaps.

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. 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). In the models, the dependant variables are THW in car-following, and merge gap in lane changing. The analyses were performed using the Python package 'statsmodels' (Seabold & Perktold, 2010).

3. Results

The results of this study are structured following the presented research questions in section 1. Prior to that we present the questionnaires results.

3.1. *Questionnaires*

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 and 84. The average and standard deviations of the trust scores of all participants were $M = 54.5$ ($SD = 8.8$) and $M = 53.7$ ($SD = 8.5$) for car-following and lane changing, respectively. These results indicate that the mean trust scores were moderately high.

Simulation Sickness Questionnaire (SSQ): The score of SSQ reflects the symptomatology of participants' experience during the

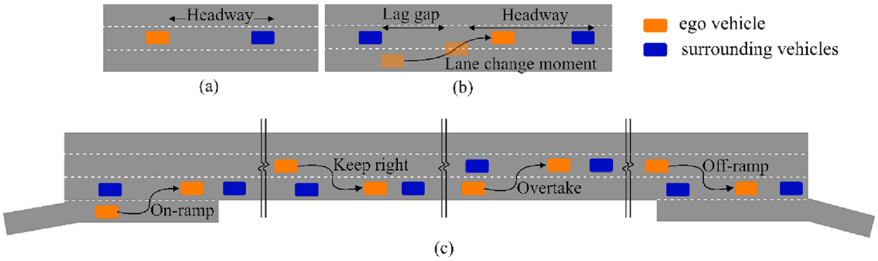


Fig. 5. (a) Headway during car-following and (b) lead and lag gaps during lane changing, (c) different lane changing manoeuvres.

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 ($M = 29.1$; $SD = 28.5$).

Presence Questionnaire (PQ): The PQ score could range between 19 and 133 summing the 19 responses of the core questions. Higher scores mean better presence of subjects during the experiment. The average presence score was $M = 93$ ($SD = 14.8$). This is higher-than-average amount of presence during the drive in the driving simulator.

Familiarity with automation: Participants were also asked about their familiarity with automation technology. 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". Additionally, only 4 participants worked in a field directly related to CAVs. This category was also merged with the group following the CAV developments. Therefore, three categories were defined as "Not familiar", "Fairy familiar", and "Very familiar".

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

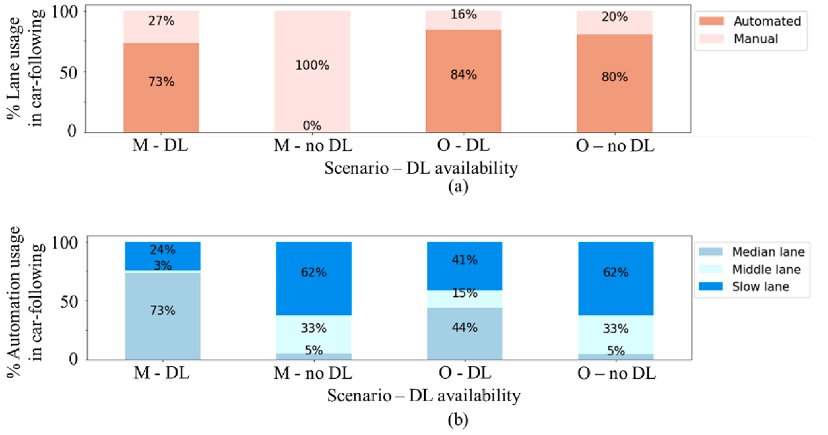
3.2. What is the impact of DL presence on the preference to use automation in car-following and lane change manoeuvres?

Fig. 6(a) 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.

Fig. 6(b) 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. Although the presence of a DL does not influence drivers' preferences to use automation (Fig. 6(a), O-DL and O-no DL), it motivates them to drive on the median lane more often (Fig. 6(b), O-DL and M-DL).

Considering the lane change manoeuvres, Fig. 7 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 Fig. 7. Moreover, the number of off-ramp diverge gaps were very low in our study. This 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 1200 m, 600 m, 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. A total of 344 lane change manoeuvres were performed. Drivers preferred to perform automated lane-change when overtaking and when keeping right (discretionary lane changes). While, at on-ramps (mandatory lane changes) there is a marginal difference between the percentages of manual and automated lane change (49 % and 51 %).

We plotted the preference to use automation against the order of road segments that was driven in *Optional* scenario. The aim was to



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

Fig. 6. (a) Preference of using automation and (b) lane utilization in car-following (THW $\leq$ 3.0 s) based on scenario and DL availability.

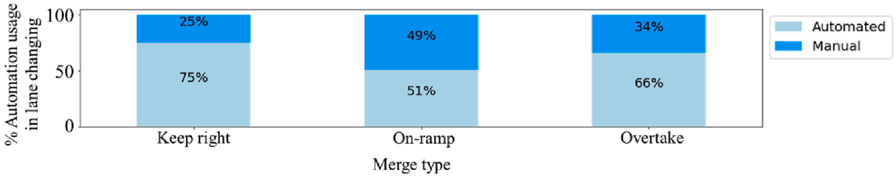


Fig. 7. Preference to use automation based on merge type on NLs in *Optional* scenario.

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 segments without a DL (segments 1 and 3). Fig. 8 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.

Next, we estimated LMMs to investigate the predictors of drivers' preference to use automation in car-following and lane changing manoeuvres, taking into account drivers' characteristics such as drivers' age, gender, education, familiarity with automation, and trust in automation, derived from the questionnaires (Table 1 and Table 2). We only considered observations on NLs in *Optional* scenario since the drivers could not choose their driving mode in *Mandatory* scenario or on DLs.

Table 1 presents the results of the LMM with binary outcome considering the observations on NLs in *Optional* scenario. Drivers who are fairly familiar or very familiar with CAVs, tend to use automation in car-following significantly more than those who are not familiar with CAVs. Also, drivers with postgraduate education level are more likely to use automation. In terms of age effects, the results show that middle aged (40–65) and elderly (65–80) drivers use automation in car-following significantly more compared to younger drivers (20–40). 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 (0.0159).

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 2). 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, elderly drivers (65–80 years old), preferred more automated overtaking compared to the younger age groups (20–40 years old). For keep right manoeuvres, the LMM showed no significant predictor in drivers' preference to automation use. Other independent variables mentioned above (gender, education level, and trust in automation in lane changing) were not significant predictors of drivers' preferences to use automation in lane changing manoeuvres.

3.3. What is the impact of the driving mode and the presence of a DL on the car-following THW?

The descriptive statistics of car-following speed is presented in Table 3. 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.

Next, to study the car-following observations longitudinal manoeuvres were divided into three different groups based on the size of THW: a) free flow when the THW is larger than 3 s 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 3 s, and c) critical car-following when the THW is equal or smaller than 1.5 s. As mentioned earlier, the average THW during capacity conditions of Dutch freeways is approximately equal to 1.5 s, which represents a capacity of 2.400 veh/hr/lane (Grontmij, 2015). Therefore, the THW $\leq$ 1.5 s was chosen as the critical THW from the aspect of capacity. Moreover, car-following with THWs around 1.5 s, increases the driver's perception of risk without making the driving task appear unrealistic (Tomasevic, Young, Horberry, & Fildes, 2022).

We estimated LMMs to compare the car-following (THW $\leq$ 3 s) and critical car-following (THW $\leq$ 1.5 s) behaviour in different modes (automated vs. manual) and lane types (DL vs. NLs) taking into account drivers' characteristics (Table 4). Here we considered all observations in both scenarios and both lane types.

As it can be seen in Table 4(a), when automated driving takes place on a DL, drivers follow the lead vehicle more closely. 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 $\leq$ 1.5 s (Table 4 (b)). In line with the results for car-following (THW $\leq$ 3 s), lane type and driving speed significantly affect the critical car-following. Moreover, drivers tend to keep smaller critical THWs when driving in manual mode.

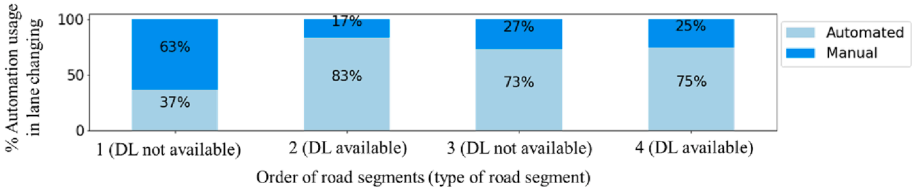


Fig. 8. Frequency of automated lane changes in the different road segments in Optional scenario.

Table 1
Drivers' preference to use automation in car-following in *Optional* scenario – LMM.

	Categories	Coefficient	p-value	Z
Intercept		−0.6773	<.001*	−5.388
Familiarity	Fairly familiar (vs. Not familiar)	0.6245	<.001*	9.468
	Very familiar (vs. Not familiar)	0.1770	.006*	2.725
Education	Postgraduate (vs. Undergraduate)	0.2999	<.001*	6.815
Age	40–65 (vs 20–40)	1.5839	<.001*	28.377
	65–80 (vs 20–40)	0.7447	<.001*	13.923
Trust		0.0159	<.001*	6.176
Statistics				
Log-likelihood		−7798.3		
AIC		15604.6		

* Significant at 95% confidence level.

Table 2
Drivers' preferences to use automation in lane change manoeuvres – LMM.

		Overtake			On-ramp		
	Categories	Coef.	p-value	Z	Coef.	p-value	Z
Intercept		−3.0881	.008*	−2.674	−2.9722	.002*	−3.037
Age group	40–65 (vs 20–40)	0.7817	.178	1.346			
	65–80 (vs 20–40)	1.9443	.016*	2.409			
Merge gap (s)		0.9864	.003*	3.010	1.0373	.002*	3.125
Statistics							
Log-likelihood		−45.90			−57.2		
AIC		95.81			118.4		

* Significant at 95% confidence level.

Table 3
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

Table 4
THWs for car-following – LMM.

		(a)			(b)		
		Car-following (THW ≤ 3 s)			Critical car-following (THW ≤ 1.5 s)		
	Categories	Coef.	p-value	Z	Coef.	p-value	Z
Intercept		0.384	<.001*	6.694	0.629	<.001*	21.489
Lane type	DL (vs. NL)	−0.159	<.001*	−21.364	−0.058	<.001*	−12.401
Speed		0.050	<.001*	48.633	0.019	<.001*	28.706
Driving mode	Manual (vs. Automated)				−0.086	.008*	−2.643
Statistics							
Log-likelihood		−39076.18			1335.94		
AIC		78160.36			−2663.88		

* Significant at 95% confidence level.

3.4. *What is the impact of the driving mode and the presence of a DL on the gap acceptance in lane changing manoeuvres?*

Table 5 shows the number of lane change manoeuvres per merge type in *Mandatory* versus *Optional* scenarios. One observation represents one lane change manoeuvre. 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 which were excluded from the analysis. 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 exceeded manual

Table 5
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
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

lane changes (approximately 70 % of total lane changes were executed in automated mode). This suggests a greater tendency among drivers to change lanes in automated mode, particularly when keeping right or overtaking. However, when merging from an on-ramp in the *Optional* scenario, there was no clear preference for driving mode.

Three LMMs were estimated to investigate the effects of scenario variables and demographics on the accepted lane change gaps. According to Table 6, driving mode influences the size of the accepted gap. In both on-ramp and overtake lane changes, the accepted gap is smaller in manual mode as shown in Table 6. Obviously, lane type is not included in the model for 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.

Keep right lane changes were also studied. No specific trend was found in these type of lane changes.

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. The results are discussed below for each of the research questions proposed in Section 1.

4.1. *The impact of DL presence on the preference to use automation in car-following and lane changing manoeuvres*

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. However, the presence of a DL motivated the drivers to drive more on the median lane which was the DL, especially in *Mandatory* scenario, since the median lane was the only lane that they could drive in automated mode. Therefore, the DL motivated drivers to drive on the median lane, but could not increase their tendency to use automation if automation was allowed on all lanes (*Optional* scenario). On the other hand, Linear Mixed Models (LMM) revealed additional predictors of automation use in car-following. Confirming the results of Kadylak, Cotten, & Fennell, (2021) and Nielsen and Haustein (2018), who stated that higher education has a positive impact on acceptance of automation technology, this study suggests that drivers with postgraduate 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 and elderly drivers were more likely to use automation compared to younger drivers. The reason could be the fact that younger drivers are more confident in their driving skills and less interested to be assisted by automation (Piao et al., 2005). Finally, familiarity with CAVs had a positive impact on drivers' preference to use automation in car-following.

During the drives in the driving simulator, participants changed lanes at on- and off-ramps, 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 changes, we considered observations in *Optional* scenario and on normal lanes, where the drivers could choose their driving mode in lane changing.

The findings revealed that drivers exhibit a higher likelihood of utilizing automation over manual mode during keep right and overtaking manoeuvres (discretionary lane changing). However, when merging onto the motorway via an on-ramp (mandatory lane

Table 6
Accepted gaps for lane changing – LMM.

		On-ramp			Overtake		
	Categories	Coef.	p-value	Z	Coef.	p-value	Z
Intercept		3.171	<.001[*]	26.750	3.430	<.001[*]	22.350
Driving mode	Manual (vs. Automated)	−0.530	<.001[*]	−3.955	−0.623	.001[*]	−3.301
Lane type	DL (vs. NL)				−0.444	<.001[*]	−3.889
Statistics							
Log-likelihood		−209.52			−400.0		
AIC		423.04			808.0		

[*] Significant at 95 % confidence level.

changing), no significant differences were observed in driving mode preferences.

Additionally, the LMM showed that interest in automated lane change increased with age. Elderly drivers (65–80 years old) were more likely to prefer automated mode in overtaking manoeuvres. This result corroborates the findings of Rödel, Stadler, Meschtscherjakov, & Tscheligi, (2014) and Piao et al. (2005) that found that elderly 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 elderly drivers in automated lane change could relate to their higher simulation sickness, which might deter them from resuming manual control during lane changes. On the other hand, the lateral speed in automated lane changes was moderately low and closer to elderly drivers' average lateral speed when performing manual lane changes. Thus, automated lane change with lower lateral speed appeared to be more preferred by elderly drivers than by younger ones. Therefore, 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 and on-ramp manoeuvres which shows drivers prefer to use automated lane change when the situation is less risky (Tomasevic, Young, Horberry, & Fildes, 2022) and a large gap is available.

Regarding keep right manoeuvres, the LMM showed no significant predictor of automation use.

4.2. *The impact of the driving mode and the presence of a DL on the car-following THW*

It was also investigated if drivers adopt shorter THWs when driving in automated mode compared to manual mode. LMMs compared the THWs in car-following while in automated and manual mode and revealed that drivers tend to follow a lead vehicle keeping larger THWs in automated mode. This would have positive impacts on traffic safety but might deteriorate traffic efficiency. Accepting larger THWs in car-following 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, Young, Horberry, & Fildes, 2022) and switch to automation when it is less crowded. Thus, the THWs 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 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).

Although drivers preferred to adopt larger THWs in automated mode, they kept shorter THWs when they were driving on dedicated lanes, knowing that all vehicles are automated. This aligns with previous research suggesting that drivers tend to follow their leader more closely when the leading vehicle is automated (Rahmati et al., 2019).

4.3. *The impact of the driving mode and the presence of a DL on the gap acceptance in lane changing manoeuvres*

The study also examined whether drivers exhibit a preference for shorter merge gaps when driving in automated mode compared to manual mode. LMMs were employed to compare the merging gaps during lane changes between automated and manual modes, revealing that drivers tend to merge into larger gaps when changing lane in an automated mode. However, the larger merge gaps stems from drivers' decisions on when to execute a lane change in automated mode. The results showed drivers are more likely to perform the lane change in automated mode if the merge gap is larger. So, in line with car-following, drivers perform automated lane changes in less crowded and complex situations (Horswill and McKenna, 1999; Basu et al., 2017).

While drivers generally exhibit a more conservative driving style when relinquishing control to the automated vehicle, they accept smaller gaps when changing lanes towards a dedicated lane where they merge between two automated vehicles. This aligns with the findings of a field test indicating that drivers merge closer in front of recognizable automated vehicles (Soni et al., 2022). However, considering the findings indicating higher driving speeds on DLs, accepting smaller gaps when changing lanes towards DLs could increase the risk of collision.

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. 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 lane changes right after 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. Elderly 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 increased drivers' preference to use automation in car-following marginally. 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 virtual reality environment was chosen 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 (40 %). 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. Additionally, we acknowledge the moderately low sample size of this study and recognize the different sample sizes in the literature ranging from 30 to over 100. It is imperative for future research to consider larger sample sizes to better account for the heterogeneity among participants, to understand the complexities of driver behaviour, and to improve the generalizability of findings.

Finally, the analysis excluded off-ramp lane changes due to their limited occurrences. Therefore, further research is needed on this driving manoeuvre.

CRediT authorship contribution statement

Solmaz Razmi Rad: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haneen Farah:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Henk Taale:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Bart van Arem:** Writing – review & editing, Supervision. **Serge P. Hoogendoorn:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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