Car-following behavioral adaptation when driving next to automated vehicles on a dedicated lane on motorways: A driving simulator study in the Netherlands

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ABSTRACT

Automated vehicles (AVs) are expected to improve traffic flow efficiency and safety. The deployment of AVs on motorways is expected to be the first step in their implementation. One of the main concerns is how human drivers will interact with AVs. Dedicating specific lanes to AVs have been suggested as a possible solution. However, there is still a lack of evidence-based research on the consequence of dedicated lanes for AVs on human drivers' behavior. To bridge this research gap, a driving simulator experiment was conducted to investigate the behavior of human drivers exposed to different road design configurations of dedicated lanes on motorways. The experiment sample consisted of 34 (13 female) licensed drivers in the age range of 20–30. A repeated measures ANOVA was applied, which revealed that the type of separation between the dedicated lane and the other lanes has a significant influence on the behavior of human drivers driving in the proximity of AV platoons. Human drivers maintained a significantly lower time headway (THW) when driving in the proximity of a continuous access dedicated lane as compared to a limited-access dedicated lane with a guardrail separation for AV platoons. A similar result was found for the limited-access dedicated lane in comparison to the limited-access dedicated lane with guardrail separation. Moreover, the results regarding the empirical relationships between THW and sociodemographic variables indicate a significant THW difference between males and females as well as a significant inverse relationship between THW and the years of driving experience.

1. Introduction

The application of automated vehicles (AVs) represents a technological leap forward that can dramatically change how people approach mobility (Howard & Dai, 2014). It is expected that AVs will reduce traffic congestion, road accidents, and fuel consumption (Fagnant & Kockelman, 2015). Connected and Automated Vehicles (CAVs) have the potential to improve traffic flow by driving with short time gaps between vehicles. With strong belief in the potential benefits of AVs that can bring about a significant change in road mobility, the Dutch government wants to take the lead in the deployment of AVs (Alkim, 2018). To keep up with the technological developments in the field of automation, the road infrastructure will need...
to upgrade its physical and digital design accordingly (Farah, Erkens, Alkim, & van Arem, 2018; Isaac, 2016; Lu, Madadi, Farah, Snelder, Annema, & van Arem, 2019). The most beneficial built environment for automated driving is a low complexity environment, such as motorways. However, there are still many uncertainties regarding the deployment of AVs on motorways. An in-depth understanding and consensus are necessary on how to adapt the infrastructure of motorways to AVs.

The most contentious issue involves the choice between mixing automated traffic freely with conventional non-automated vehicles and dedicating a unique infrastructure to AVs (Shladover, 2005). Various studies suggest the implementation of dedicated lanes for AVs as a solution for the difficulties that may occur in a mixed traffic situation (Kockelman, Avery, Bansal, Boyles, Bujanovic, Choudhary, & Helsel, 2016; Lumiaho & Malin, 2016; McDonald & Rodier, 2015; Milakis, Snelder, van Arem, van Wee, & de Almeida Correia, 2017; Shladover, 2005). This is because the benefits of AVs can be maximized on a reserved lane where they are not interrupted by non-equipped vehicles (Friedrich, 2016). Although a dedicated lane is often mentioned as a solution, scientific research on the design of these lanes is inadequate (Rad, Farah, Taale, van Arem, & Hoogendoorn, 2020).

The following section reviews first the scientific literature on the design of dedicated lanes, then presents the different research methods used in previous studies to investigate behavioral adaptation of human drivers in the vicinity of dedicated lanes, followed by the relationship between socio-demographic variables and driving behavior and finally, the identified research gaps and research questions.

2. Literature review

2.1. Design of dedicated lanes

The literature often mentions positioning the automated lane on the left side of the road (with right-hand traffic) (Ran, Leight, & Chang, 1999; Tsao, Hall, & Shladover, 1993). However, there is inadequate scientific research on the reasoning. Regarding access to and from the dedicated lane, two options are possible: continuous access or limited access. Continuous access allows eligible vehicles to enter or exit the dedicated lane continuously from the other regular lanes. Limited-access lanes have specified ingress and egress locations that permit lane-changing maneuvers to the dedicated lane and are separated from the other motorway lanes by buffer zones or barriers. The literature indicates that limited access would be desirable from the perspective of safety (Hitchcock, 1991; Tsao et al., 1993). However, these safety concerns contradict the study results of Jang, Chung, Ragland, and Chan (2009), who investigated the safety issues of high occupancy vehicle lanes (HOV) in Canada. Their study showed that HOV lanes with limited access offer no safety advantages over those with continuous access. Regarding the design of limited-access lanes, there are multiple options. Yim, Miller, Hellman, and Sharafsaleh (1997), propose to have a separated lane with a transition lane that provides the opportunity to check whether the entering vehicles are equipped with automated functionalities. The National Automated Highway System Consortium provides three options with respect to the separation: the virtual barrier, buffer zone, and physical barrier (National Automated Highway Systems Consortium, 1997). Awan et al. (2018) have shown the impacts of different separation methods on the behavior of drivers. They found that harder separation is more effective in restricting lane usage. However, it also made drivers feel trapped (Varaiya, 1994). Earlier, researchers also found more road accidents near the beginning of motorway sections with a barrier as compared to sections without a barrier (Tsao, Hall, & Hongola, 1994).

2.2. Methods for driving behavior research

There are two commonly used approaches to examine driving behavioral adaptation to road infrastructure and physical environment: using driving simulators and through field studies. Driving simulators have been proven to be a suitable solution for testing how road design solutions are perceived and how driving behavior will be influenced by different road infrastructures (Llorca & Farah, 2016; Mullen, Charlton, Devlin, & Bedard, 2011; Niezgoda, Kamiński, Ucińska, & Kruzewski, 2011; Risto & Martens, 2014). When driving simulator research is explored in the field of AVs, the majority of these studies focus on the human-machine interaction and the behavioral adaptation of AVs drivers (Merat, Jamson, Lai, & Carsten, 2012; Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Young & Stanton, 2007). Research on the interaction between AVs and other human-driven vehicles is not extensive. To the best of our knowledge, only a few studies focus on this topic. Gouy (2013) conducted a study using a driving simulator to test the car-following behavior of manual vehicles (MVs) in the presence of AVs to assess behavioral adaptation in a more controlled environment. In this study, participants drove behind a lead vehicle in the vicinity of AV platoons exhibiting different headway characteristics. Gouy (2013) found a significant difference in the time headway (THW) of MVs in the presence of the platoons. The presence of truck platoons maintaining short THWs in traffic influenced the mean THW of the MV drivers. Field studies on behavioral adaptation are limited. Recently, Rahmati, Khajeh Hosseini, Talebpour, Swain, and Nelson (2019) conducted a field experiment to study the car-following behavior in human–human and human–AV interactions. The authors considered two scenarios of a platoon composed of three vehicles. In both scenarios, the leader of the platoon followed a series of speed profiles extracted from the Next Generation Simulation dataset (NGSIM). The second vehicle was either a MV or an AV, while the third vehicle was a MV. The researchers investigated the changes in the driving behavior of the third (human driven) vehicle. A statistically significant difference was found between human drivers’ behaviors in these two scenarios. In addition, human drivers felt more comfortable following the
AV. The European project KONVOI investigated the changes in the behavior of AV and MV drivers who overtook the truck platoon. The results showed that drivers who drove with a small THW in a platoon significantly chose a shorter THW in the subsequent manually driven road section (Skottke, 2007). This carry-over effect that resulted from the reduced THW changed drivers’ behavior but not their judgments on a suitable THW, suggesting that behavioral adaptation can occur unconsciously. Thus, based on the literature, it can be concluded that there might be a behavioral adaptation when human drivers interact with AVs. However, these studies did not incorporate different infrastructural design configurations into consideration. Therefore, it is unclear under what infrastructural design configurations behavioral adaptation occurs.

2.3. Sociodemographic characteristics and driving behavior

Several studies were conducted regarding the relationship between sociodemographic characteristics and driving behavior (Bener & Crundall, 2008; Farah, 2011; Lewis-Evans, De Waard, & Brookhuis, 2010; Peplinska, Wyszomirska-Gora, Polomski, & Szulc, 2015; Rajalin, Hassel, & Summala, 1997; van Winsum, 1996). They concerned age and gender as variables that influence driving behavior, involvement in accidents, risk perception, and traffic violations. The analysis of Peplinska et al. (2015) revealed that among a variety of sociodemographic variables, age, gender, and the duration of having a driving license had a statistically significant correlation with dangerous driver syndrome. Bener and Crundall (2008) found that young males tend to be more involved in risky driving behavior. Farah (2011) investigated overtaking behavior and found significant differences in the THW regarding gender and age. Rajalin et al. (1997) who investigated the following gaps also found significant differences regarding gender and age. Nevertheless, studies testing the influence of driving experience on car-following behavior (Lewis-Evans et al., 2010) or the THW (van Winsum, 1996) did not find such significant relationships as compared to age and gender.

2.4. Research gaps and research questions

To summarize, earlier research studies on driving behavior adaptation mainly focused on human-machine interaction and the behavioral adaptation of AVs’ drivers. To date, few studies have evaluated the impacts of the interaction between AVs and other road users in scenarios where there is a dedicated lane. There is also scarce knowledge regarding the impact of the design of these lanes on MV drivers’ behavioral adaptation. In the literature, sociodemographic variables were found to affect driver behavior significantly. Therefore, it would be not only logical but also important to assume that these sociodemographic factors might influence the MV drivers’ behavioral adaptation as well.

To bridge these gaps, this study aims to investigate the human driver behavioral adaptation when driving in the proximity of a dedicated lane with AV platoons. To fulfill this aim, the study will investigate the following research questions:

(1) How is the behavior of MV drivers be influenced when driving in the proximity of a motorway dedicated lane with CAV platoons?
(2) How do different configurations of dedicated lane designs affect this behavioral adaptation?
(3) How do sociodemographic characteristics (such as gender, age, and years of driving experience) influence the MV drivers’ behavioral adaptation in these scenarios?

The hypothesis is that drivers will adapt their driving behavior when driving in proximity to a platoon of AVs on a dedicated lane by reducing their THW. It is expected that the effect will be different for different types of separation and varying sociodemographic characteristics of drivers. The primary variable that is investigated in this research regarding behavioral change during driving is the THW drivers adopt in different scenarios, which is measured in the driving simulator experiment. Respondents’ attitudes toward technological development and their perceived safety feeling regarding different lane designs will also be investigated to gain a better understanding and insights behind possible behavioral adaptations.

3. Methodology

A driving simulator experiment was designed to evaluate the impact of different configurations of dedicated lane design on the THW adaptation of MV drivers. The upcoming Section 3.1 explores different possible design configurations for the dedicated lane, followed by the description of the driving simulator experiment apparatus in Section 3.2. The data collection process is explained in Section 3.3 and the measure of THW and the statistical method applied in this study are presented in Section 3.4. Section 3.5 describes the sample of the participants and preliminary results of the pre-experiment and post experiment questionnaires.

3.1. Design configurations of the dedicated lane

Based on the assumption that mixed traffic will be the situation in the near future as long as the penetration level of AVs is low (Rad et al., 2020), three key aspects of road design were considered when developing the design configurations for the dedicated lanes: the position of the lane, access to and from the dedicated lane, and the type of separation between lanes.
Logical reasoning can substantiate that the throughput of lanes for AVs will be higher than the throughput of regular lanes (i.e., lanes for traditional traffic). Therefore, it is logical to place the dedicated lane for AVs on the left side of the road with right-hand traffic. This design will also be consistent with the positioning of truck lanes on the right side of the road. This is also in line with the previous design concepts for dedicated lanes (Hitchcock, 1991).

Regarding access to and from the dedicated lane, there are two possible options, either continuous access or limited access. A minimum number of two lanes for MVs will be necessary to enable passing maneuvers among faster and slower manually operated vehicles. This restriction will be hard to meet on the current motorway system of the Netherlands since most of the motorways consist of 2 or 3 lanes in each direction. In the literature, it is proposed that entry ramps should be spaced with a distance of approximately 3.5 km and exit-ramps should be located approximately 2 km after the entry ramp to provide adequate space for vehicles to properly execute entry and exit maneuvers (O’Brien, Schulze, & Lima, 1994). It should be pointed out that when all the merging maneuvers are concentrated on specified entry- and exit ramps bottlenecks might occur around these ramps (Cheon, 2003; van Beinum, Farah, Wegman, & Hoogendoorn, 2018). Therefore, both scenarios (continuous access and limited access) were included in this research.

Regarding the way the dedicated lane is separated from the other lanes, three main commonly options were considered: virtual barriers, buffer zone, and physical barrier. A buffer zone is a narrow paint stripe, whereas a physical barrier is a physical separation like a guardrail. The benefits of a physical barrier are preventing collisions of MVs with AVs and vice versa, and the feeling of safety perceived by human drivers due to being physically separated from the faster moving traffic driving on the other lanes. The downsides of a physical barrier are the increased severity of impact in case of a collision, the occupation of extra space by the barrier and its inflexibility. Both separations were tested in this research.

Therefore, four final road design scenarios were investigated in this research: (a) a Baseline Scenario (BL), (b) a Continuous Access Lane (CAL), (c) a Limited Access Lane with buffer (LAL), and (d) a Limited Access Barrier Lane (LABL). The layouts of these scenarios are shown in Fig. 1. The baseline scenario does not incorporate any AVs and represents the state of current roads.

3.2. Apparatus

This study utilized the fixed-base, medium-fidelity driving simulator located at the faculty of Civil Engineering and Geosciences, at the Delft University of Technology. The driving simulator consisted of a mock dashboard with three high-resolution screens, which displayed both side windows and the windshield, providing an approximately 180° field of view, with a Fanatec steering wheel, pedals, and blinker control. A picture of a participant driving in the driving simulator can be seen in Fig. 2.

All four designed scenarios had identical environments with respect to buildings, trees and landscapes. The only aspect that was changed in the scenarios was the design configuration of the dedicated lane as illustrated in Fig. 1. The road design in the four scenarios was based on the Dutch road design standards, Richtlijn Ontwerp Autosnelwegen 2014 (Rijkswaterstaat, 2014) (e.g. aspects such as radius of a curve, lane width, road markings). The roads were developed using SketchUp Pro and then exported as FBX files which could be imported into Unity. The other elements in the surroundings of the scenarios such as trees, buildings and hills, consisted of the standard assets from the GreenDino’s driving simulator package. The road was straight and continuous with a typical Dutch landscape – a flat open area, with a limited number of trees, and some scattered buildings with limited distractions alongside the road. Screenshots of the four scenarios developed in Unity can be seen in Fig. 3.

3.3. Data collection procedure

Prior to the driving simulator experiment, respondents were requested to fill in a questionnaire concerning their sociodemographic characteristics (e.g., gender, year of birth, nationality) and their attitudes towards technology. The questionnaire regarding their attitudes towards technological developments were rated on a 5-point Likert scale from strongly disagree to

![Fig. 1. Design scenarios of the dedicated lane for AVs (red rectangles represent human driven vehicles while blue rectangles represent AVs). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
strongly agree and included three questions: ‘I am very technology-oriented’, ‘I believe technological developments will have a positive impact on society’, and ‘I believe the automated vehicle will have a positive impact on society’. After the driving simulator experiment, they were requested to fill in another questionnaire that asked about their experience in the driving simulator and whether they have experienced any general discomfort, nausea, discomfort in their stomach and vertigo. These questions were answered using yes or no choices and helped to understand whether they had any discomfort with the driving simulator (Fisher, Rizzo, Caird, & Lee, 2011).

Before the simulator experiment, an informed consent was obtained from each participant declaring their voluntary participation in the experiment and their awareness of the possible risks of simulator sickness. They were informed that the experiment was about AVs but not about the exact measurements that will be taken. The researchers also obtained the approval of the ethical committee of the Delft University of Technology. The data collected in this research are listed in Table 1.

Participants were asked to drive 5 min in an environment unrelated to the experiment to become familiar with the driving simulator and to get rid of the fun factor (Crundall, Andrews, Van Loon, & Chapman, 2010). The experiment was composed of four driving scenarios (BL, LABL, CAL, and LAL). Each scenario took about 12 min to be completed. The first minute of the data was deleted because it took drivers some time to reach the headway they desired and accelerate to their desired speed. Participants were instructed to follow the red car in front of them. This was the leading vehicle from which their THW was measured. The order of the scenarios was randomized between the participants to overcome the influence of the order effect. The order has been balanced in the design. Between every two scenarios, there was a short break of a few minutes depending on the needs of participants. In total, the experiment took more or less an hour to complete. The collected

![Fig. 2. Driving simulator demonstration.](image)

![Fig. 3. Screenshots of the four scenarios developed in Unity.](image)
The THW was calculated using the basic traffic flow formula (1) where \( h_i \) is the time headway, \( s_i \) is the space headway between the subject vehicle and the leading vehicle and \( v_i \) is the velocity of the subject vehicle.

\[
h_i = \frac{s_i}{v_i}
\]  

(1)

To determine whether there is a statistical difference between the four scenarios, a repeated measures ANOVA was applied. This statistical test is useful when there are multiple measurements for the same participant resulting from driving in different conditions/scenarios. It has more statistical power because it can control for errors that might occur from the variance between participants. This makes it possible to conduct reliable research with a limited number of participants, which is extraordinary beneficial in the case of a time-consuming driving simulator experiment (Frost, 2015). A challenge regarding repeated measures designs is the order effect. This implies that the result can be influenced by the order of scenarios in which the data is measured. In this experimental design, the order of the scenarios was balanced between participants to overcome the influence of this order effect. Moreover, in order to conduct a repeated measures ANOVA, the assumption of sphericity needs to be tested. Sphericity is obtained when the variances of differences between all combinations are equal. If the assumption is violated, statistical methods that adjust for the lack of sphericity need to be used.

The empirical relationship between THW and sociodemographic variables was analyzed using Mixed ANOVA, Pearson Correlation test (combine with Fisher’s z), and repeated measures correlation test. According to the literature, the sociodemographic factors that can influence the THW are gender, age, and the number of years of driving experience. A Mixed ANOVA was conducted to evaluate whether the participants in different gender group have different THW in the four road design scenarios. And, whether such THW was more significant in some groups than others i.e. whether there was an interaction between gender and road design scenarios. Pearson Correlation test, and repeated measures correlation test were conducted to investigate the common intra-scenario association for paired continues measures such as the THW and the number of years of driving experience.

3.5. Participants

Participants had to meet three criteria to be able to participate in this experiment: drivers needed to be between 20 and 30 years old, have a valid driving license, and have at least two years of driving experience on the Dutch motorway system. These criteria were set to have a homogenous group of participants in terms of age and to exclude novice drivers. Posters with these required details were distributed at the campus of the Delft University of Technology in order to find participants for the experiment who meet the aforementioned criteria.

4. Results

4.1. Participants & questionnaire results

Overall, 35 participants from the Delft University of Technology were recruited. Out of those, 34 participants with valid response data were used for the analysis. Of these 34 participants, 13 were female and 21 were male. The driving experience ranged between 2 and 10 years (mean = 5.1 years, standard deviation = 1.5 years). Of the 34 participants, 3 participants had already driven in a driving simulator before. All participants were of Dutch nationality.

Their attitudes towards technological developments and automated vehicles were rated on a 5-point Likert scale from strongly disagree to strongly agree. The results in Fig. 4 indicate that the participants have a relatively very positive attitude towards technology and the influence of technology on society. Most of the respondents considered themselves to be techn-
Many of them believe that both technological developments and AVs will have a positive impact on society. The highly technology-oriented sample could be explained by the fact that the participants were recruited from the Delft University of Technology.

Furthermore, we asked about their experience regarding the driving simulator experiment in the post-experiment questionnaire. While 27 respondents did not experience any discomfort during the experiment, 7 respondents felt vertigo, stomach awareness, or nausea.

4.2. Repeated ANOVA for THW in different road design scenarios

The results of measuring the THW on different road design scenarios are presented in Table 2. As can be seen, the average THW for the LAL and the CAL scenarios are lower than the averages for BL scenario and the LABL scenario. A repeated ANOVA was conducted to further explore these differences.

Before conducting the repeated ANOVA analysis, Mauchly’s Test of Sphericity was applied. The result of the Sphericity test indicated that the assumption of sphericity had been violated ($X^2(2) = 683.109, p < 0.0005$). Therefore, a repeated measures ANOVA with a Greenhouse-Geisser correction was used to determine whether there is a statistically significant difference between the four scenarios. The differences in mean values with respect to the baseline measurement were 0.76(CAL), 0.90(LAL), and 0.15(LABL) as shown in Table 2. The final results show that the mean THW differs significantly between the four different scenarios ($F(2.014, 6193.535) = 1089.296, p < 0.05$). Post hoc tests using the Bonferroni correction revealed that the differences between every two scenarios were significant ($p < 0.05$), except for the THW difference between the BL and the LABL. The effect size was estimated by Partial Eta Squared in the SPSS program, which is 0.262.

4.3. Results of correlation between THW and gender in different road design scenarios

When these variables were subjected to visual inspection, some patterns could be identified. As shown in Fig. 6, the average THW of males is distinctly lower than the average THW of females. It can also be noticed that the standard deviation (SD) of the THW for females is larger compared to that of males. To assess if the participants in different gender groups had different THW in the four road design scenarios and whether THW was more significant in some groups than others, a Mixed ANOVA was conducted in SPSS to account for the repeated measures.

According to the results there is a significant difference across the four scenarios, $F(1, 768) = 113.447, p = <0.001$. THW values are significantly lower for CAL scenario. A significant effect for gender was obtained, $F(1, 768) = 15.978, p < 0.001$, though this was a weak effect (Eta-squared = 0.02). THW values were significantly lower for males (ave. = 3.226) than females (ave. = 3.793). There was also a significant interaction between scenarios and gender group, $F(1, 768) = 6.249, p = 0.013$, though this was a weak effect (Eta-squared = 0.008). Examination of Fig. 7, which presents the estimated marginal means of THW, indicates that females decreased their THW values in LABL scenario compared to the baseline scenario. However, males didn’t have much of a change. The difference of THW values of males between CAL scenario and LAL scenario was bigger than THW of females.

### Table 2

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average THW(s)</th>
<th>Std. THW (s)</th>
<th>Ave. THW Diff. vs. BL scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Scenario (BL)</td>
<td>3.24 s</td>
<td>1.55 s</td>
<td>–</td>
</tr>
<tr>
<td>Continuous Access Lane (CAL)</td>
<td>2.47 s</td>
<td>1.26 s</td>
<td>0.76</td>
</tr>
<tr>
<td>Limited Access Lane with buffer (LAL)</td>
<td>2.69 s</td>
<td>1.33 s</td>
<td>0.90</td>
</tr>
<tr>
<td>Limited Access Barrier Lane (LABL)</td>
<td>3.17 s</td>
<td>1.56 s</td>
<td>0.15</td>
</tr>
</tbody>
</table>
4.4. Results of correlation between THW and years of driving experience in different road design scenarios

A relation between the average THW and the number of years of driving experience was found, as illustrated in Fig. 8. In general, the fewer the years of driving experience, the higher the THW. Nevertheless, 2 years and 10 years of driving experience are only represented by one participant in this dataset. Therefore, it could also be possible that this pattern is based on coincidence. A Pearson correlation analysis revealed a significant and negative relationship between THW and the number of years of driving experience in all scenarios with $r_{BL} = -0.203$, $p < 0.001$; $r_{CAL} = -0.227$, $p < 0.001$; $r_{LAL} = -0.271$, $p < 0.001$; $r_{LABL} = -0.179$, $p < 0.001$. The results would imply that when the number of years of driving experience increases, the THW decreases. Among these four scenarios, the LABL scenario has the smallest $r$ value ($r_{LABL} = -0.179$, $p < 0.001$).

To further consider the scenarios impact on the correlation between THW and years of driving experience, a repeated measures correlation (rmcorr) was performed with R. It accounted for dependence among observations using analysis of covariance (ANCOVA) to statistically adjust for inter-scenario variability. The results showed that $r = -0.212$ ($p < 0.001$).
which indicated the negative correlation between THW and years of driving experience after considering inter-scenario variability. This result is consistent with the results of the Pearson correlation analysis.

4.5. Discussion and conclusions

Several studies have found that changes in the road infrastructure and physical environment result in changes in driving behavior (Rudin-Brown & Ian Noy, 2002). However, evidence-based knowledge regarding the design of dedicated lanes for AVs and their implications on the behavior of human driven vehicles is limited and restricted to conceptual designs only with no empirical-based evidence (Rad et al., 2020). To fill this gap, this study investigated the effects of three design configurations of a dedicated lane for AVs on the behavior of MV drivers traveling in the proximity of AVs driving on the dedicated lane.

Based on the repeated measures ANOVA with Greenhouse-Geisser correction analysis, a significant change in the THWs of MVs was observed during car-following in the different design configurations of the dedicated lane. The results show that drivers of MVs drove with a significantly lower THW from the vehicle in front when driving in the proximity of an AV platoon on continuous access dedicated lane as compared to the baseline scenario (i.e. when drivers of MVs were not exposed to a platoon of AVs driving on a dedicated lane). Similar results were found for a dedicated lane with limited access when using a continuous line as a separation. However, the observed THW on the limited access lane with a guardrail as a separation had the smallest difference to the observed THW in the baseline scenario. The reduction of the THW of the MV drivers could negatively affect traffic safety (Vogel, 2003), particularly considering the longer reaction time of human drivers compared to that of AVs.

Moreover, statistical analyses were applied to explore the empirical relationships between the mean THW and sociodemographic variables. Considering that all the respondents were within the age of 20–30, we did not expect age to be an essential indicator in this case. Therefore, only gender and the number of years of driving experience were investigated. A Mixed ANOVA was used to test the empirical relationship between THW and gender, and a bivariate Person test and a repeated measures correlation estimation were used to test the empirical relationship between THW and the number of years of driving experience. The results revealed that the average THW and the standard deviation of THW of males were distinctly lower in comparison to females, which is in accordance with previous literature (Farah, 2011). This pattern is in line with the investigated literature where males express themselves in riskier driving behavior and prefer a shorter gap compared to females (Bener & Crundall, 2008). A significant inverse relationship was found between the THW and years of driving experience within the age group of 20–30 years. Nevertheless, this observed relationship is not in line with the literature, which indicated that there is no relationship between the number of years of driving experience and the THW (van Winsum, 1996).

Moreover, LABL (Separated limited access barrier lane) scenario shows the least change of THW for both gender groups and experienced drivers. It seems the safest scenario from the THW perspective comparing with other separation scenarios. However, implementing a guardrail in the highway system is very expensive and counterproductive for the flexibility of the road system. It also has a negative implication on traffic safety in case of a collision of the AV with the guardrail. The Dutch Road Authority is trying to increase flexibility over the past years and is unbundling its infrastructure (Van Loon, Walhout, & Van Der Velden, 2015). They prefer to make the infrastructure as uncomplicated as possible to make it adaptable in the
future. Implementing such a guardrail would be inefficient and not durable since it is still uncertain what the future will bring regarding AVs. A dedicated lane with limited access for AVs could be the second-best option in this case.

This research contributes to the existing literature regarding the behavioral adaptation of human drivers when interacting with AVs. It provides a useful method for further investigation of the deployment of AVs on our existing road networks.

This study indicates that road users will adapt their behavior when interacting with AVs and therefore understanding this behavioral adaptation is a key for developing and calibrating the behavioral models, e.g., microscopic simulation models. It also highlights the importance of investigating potential behavioral adaptation in other driving maneuvers, like lane-changing and gap-acceptance. Nevertheless, some limitations need to be kept in mind. First, the study was conducted in a simulated environment and not in an on-road study. Therefore, although it provides a useful tool for comparing different scenarios, the results have a relative validity and not an absolute validity (Auberlet et al., 2014). Second, the THW measured in the driving simulator was measured in free-flow traffic. It would be interesting to compare it with a more congested traffic situation. Third, only 34 valid young respondents (in the age group of 20–30 years) have participated in the driving simulator experiment. In general, the younger generation is more technology-oriented and open to new technological developments.

Further research on the behavioral adaptation of different age groups is needed. Additionally, behavioral adaptation with respect to only the THW (i.e., longitudinal behavior), and not with respect to the lane-changing behavior (i.e., lateral behavior), has been investigated. Future research should also take possible behavioral adaptation in the lateral dimension into account.

In addition, the behavioral adaptation that is measured in the driving simulator is measured over a limited time. It should be considered that this behavioral adaption is thus of a temporary nature (Stanton, 2012). The introduction of automated systems may impact drivers’ behavior, but the changes observed may develop as drivers first discover the system, learn all possibilities and limitations, and become expert users. Therefore, to conclude if this behavioral change is permanent, situations where drivers are exposed to platoons of AVs for a longer period should be investigated in order to assess the long-term effects. Finally, in this study, although the participants knew that the study is about AVs, we have not asked them if they have recognized the vehicles driving on the dedicated lane as AVs. Although, in the future, most likely AVs will not have identifiable or recognizable looks, it would still be useful to ask them at the end of the experiment if they have recognized the vehicles as AVs. Future research should take that into account.

CRediT authorship contribution statement

**Mathijs Schoenmakers:** Conceptualization, Methodology, Software, Investigation, Writing - original draft. **Dujuan Yang:** Conceptualization, Formal analysis, Supervision, Writing - review & editing, Visualization. **Haneen Farah:** Conceptualization, Supervision, Writing - review & editing.

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