The impact of a dedicated lane for connected and automated vehicles on the behavior of drivers of manual vehicles

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Abstract

This study investigates the behavioral adaptation of manual vehicle (MV) drivers in car-following and lane changing behavior when they drive next to a dedicated lane (DL) for connected and automated vehicles (CAVs). The study compares the adaptation to a mixed traffic situation, with no dedicated lane.

Fifty-one participants were asked to drive an MV in a driving simulator on a 3-lane motorway in three different traffic scenarios: (1) Base, only MVs were present in traffic, (2) Mixed, platoons of CAVs driving on any lane mixed with MVs, (3) DL, platoons of CAVs driving only on a DL. A moderate penetration rate of 43% was assumed for CAVs. During the drives, the car following headways and the accepted merging gaps by participants were collected and used for comparisons of driving behavior in different scenarios.

Based on the results, we conclude that there is no significant difference in the driving behavior between Base and Mixed scenarios for the tested penetration rate. However, in the DL scenario, MV drivers drove closer to their leaders (especially when driving on the middle lane next to the platoons) and accepted shorter gaps (up to 12.7% shorter at on-ramps) in lane changing maneuvers.

The literature suggests that dedicating a lane to CAVs improves the traffic efficiency by providing more possibilities for platooning. This study shows that implementing such a solution will affect the driving behavior of human drivers. This should be taken into consideration when evaluating the impacts of dedicated lanes on traffic efficiency and traffic safety.

Keywords: Connected and automated vehicles; dedicated lanes; behavioral adaptation; car-following; gap acceptance in lane changing

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1. Introduction

Connected and automated vehicles (CAVs) are expected to enhance both traffic efficiency by driving with shorter time headways and traffic safety by shorter reaction times [1]. However, one of the main concerns regarding their deployment is the mixed traffic situation, in which CAVs and manually driven vehicles (MVs) share the same road. A key research gap in this respect is whether MV drivers would interact differently with CAVs compared to their interaction with other MVs [2].

A field study by Rahmati et al. [3] suggests that there is a statistically significant difference between human drivers' behavior when following an automated vehicle compared to an MV. Participants were asked to perform two drives in platoons of three vehicles. The participants always drove the last vehicle in the platoon, following an automated vehicle (scenario A) or an MV (scenario B). The lead vehicle was an automated vehicle following a series of speed profiles extracted from the Next Generation Simulation dataset, NGSIM [4]. Based on the results, MV drivers felt more comfortable following an automated vehicle and drove closer to their leader if they followed an automated vehicle, compared to following an MV.

Driving simulator experiments have studied the interaction between MVs and CAVs in a mixed traffic situation [5][6][7]. Gouy et al. [5] tested the car-following behavior of MV drivers in the presence of CAV platoons in a driving simulator experiment to investigate if there is any behavioral adaptation in the car-following behavior of MV drivers. In this study, participants drove an MV and followed a lead vehicle in the vicinity of CAV platoons keeping long (1s) or short (0.3s) time headways (THWs). They found that MV drivers drove very close to, but not under their minimum preferred THW in the scenario with CAV platoons specially when CAVs kept a short THW. In a later study, Gouy et al. [6] studied the behavioral adaptation of MV drivers in car-following, this time with higher exposure time to CAV platoons and higher conspicuity of the platoons by using trucks instead of personal vehicles. Platoons of trucks kept long (1.4s) or short (0.3s) THWs. According to the results, MV drivers imitated the truck platoons' behavior by keeping significantly shorter THWs and also spent more time keeping a THW below a safety threshold of 1s. The results suggest that there can be negative behavioral adaptation when humans drive next to CAVs, especially when the exposure time and conspicuity of platoons are increased. However, the authors reported that this behavioral adaptation is not long lasting since there were no carryover effects from platoon condition with THW of 0.3s to the other one (1.4s).

Dedicating a lane to CAVs is suggested in the literature to overcome the difficulties with the mixed traffic situation [8][9][10][11][12]. However, the implications of using such a lane is still understudied [2]. Schoenmakers et al. [7] hypothesized that drivers will adapt their driving behavior when driving in proximity to a platoon of CAVs on a dedicated lane by reducing their THW and that this effect would be different for different types of separations. They conducted a driving simulator study to test this hypothesis. Participants were assigned to a car-following task in four different scenarios: a) Baseline with no CAVs, b) CAVs drove on continuous access dedicated lane, (c) CAVs drove on a limited access dedicated lane with buffer, and (d) CAVs drove on a limited access dedicated lane with barrier. The results show that compared to the baseline scenario with no CAVs, MV drivers drove with a significantly lower THW from the lead vehicle when driving on the lane adjacent to the continuous access dedicated lane and limited access dedicated lane with buffer. However, MV drivers' THWs were only marginally different in the scenario with limited access dedicated lane with barrier compared to the baseline. In fact, the barrier partially blocked the view of MV drivers towards the CAV platoons and consequently (partially) prevented the behavioral adaptation. Although barrier separated DL was shown to be the safest scenario considering the car following THW, implementing such barriers would be expensive and counterproductive for the flexibility of the road system. Moreover, more crashes happen near the beginning of highway sections with barrier compared to the sections without barrier [13].

Dedicating an existing highway lane to CAVs implies restricting MVs from using one lane of the motorway which could significantly increase their travel time if the actual share of CAVs in traffic or penetration rate (PR) of CAVs is lower than the lane saturation level [14][15]. So, exploiting the beneficial implications of a DL would only be possible when we reach to moderate PRs around 30-50% [14][15][16][17][18]. This raises the question as to how the behavioral adaptation of MV drivers at moderate PRs of CAVs would be before we can implement a DL.

Furthermore, age and gender of drivers affect driving behavior differently [19][20][21]. According to the literature, young, male drivers are more likely to follow a lead vehicle more closely [19], overtake while accepting shorter gaps [20], and perform risky maneuvers [21]. Schoenmakers et al. [7] also studied the relationships between car-following and sociodemographic variables reported in a questionnaire by participants. According to the results, the average THW and its standard deviation were distinctly lower for males than females. Given these results it is relevant to investigate the behavior of different groups of drivers (age and gender) when driving next to CAVs.

Previous research has suggested that MV drivers drive closer to their leaders when driving next to CAV platoons keeping short THWs [5][6][7]. It is suggested by these studies that the behavioral adaptation is more significant when the exposure time and conspicuity of the platoons (i.e., larger vehicles such as trucks) increase. However,

these studies assumed very large platoons, representative of high PR in situations that there is no limitation for platoon size, which is a quite unlikely scenario. Moreover, most of these studies focused on the longitudinal driving behavior and did not consider behavioral adaptation in lateral maneuvers. Further research is therefore needed to firstly examine this behavioral adaptation in both the longitudinal and lateral dynamics; secondly, to investigate if the behavioral adaptation happens at moderate PRs before implementing DLs; and thirdly, to investigate the relationship between this behavioral adaptation and characteristics of MV drivers.
Therefore, the main objective of this study is to investigate the behavioral adaptation of MV drivers in car-following and lane changing when driving next to the DL and compare that to the behavioral adaptation when driving in a mixed traffic flow at a moderate PR. It should be noted that, in this paper, CAVs refer to connected and automated vehicles which are able to drive in platoons keeping short THWs (0.3s), which corresponds to SAE levels 4 and 5 [22].
The main expectations are:

- In a mixed traffic situation and at moderate PRs (43% in this study) of CAVs the behavioral adaptation of MV drivers is negligible due to lower exposure time and scarce platoons compared to the situation with no CAV (Expectation 1).
- MV drivers adapt shorter time headways (Expectation 2a) and merging gaps (Expectation 2b) in car-following and lane changing respectively when driving next to CAV platoons concentrated on one lane.
- This behavioral adaptation is different for drivers having different demographical characteristics. (Expectation 3).

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

The rest of the paper is structured as follows. In the next section the method, the experimental setup and scenario details are described following the collection and processing of the data. The analysis method and results are provided in section 3, followed by the discussion in Section 4. Finally, Section 5 provides the main conclusions and formulates recommendations for further research.

2. Methodology

2.1 Participants

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

2.2 Apparatus

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

2.3 Design of the driving environment

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

Base: all vehicles were manual in this scenario, keeping THWs in the range of 2 to 4 seconds. Vehicles on the right lane were slower than others to motivate the participant to change lanes towards faster lanes given that one of the objectives of this study was to measure accepted gaps when changing lanes. The signage and demarcations of the driving environment was designed according to what drivers experience on a typical Dutch motorway (see Figure 1(a)).

Mixed: this scenario contained both MVs and CAVs in a mixed driving situation. The PR of CAVs was set to 43% and they could drive on any lane of the motorway in platoons of 2 to 3 vehicles. The intra-platoon and inter-platoon THWs were set to 0.3s and 2s, respectively. The signage and demarcation of the motorway did not differ with that of the Base scenario (Figure 1 (a)).

Dedicated lane: The left most lane of the motorway was dedicated to CAVs and therefore, CAVs were not allowed to drive on the other lanes. Intra-platoon and inter-platoon THWs were set to 0.3s and 2s, respectively, similar to the Mixed scenario. Also, the platoon size (2 to 3 vehicles) and the PR were similar as in the Mixed scenario (43%). To inform the participants about the dedicated lane, a buffer demarcation separating the DL and the other lanes was applied. Road signs were also added as illustrated in Figure 1 (b) to further clarify the purpose of this lane. Participants also read about the DL concept in the instruction before performing the drives.

The road sign for the DL contained a “no entry” symbol with an exception (uitgezonderd in Dutch) for CAVs. The platooning pictogram was selected based on results of a survey on symbol comprehension. A total of 455 respondents filled in the survey which consisted of different pictograms. They were asked to write down the meaning of the symbols and take an “educated guess” if they were not sure of the meaning.

Figure 1: Driving environment, (a) Base and Mixed scenario, (b) Dedicated lane scenario.

2.4 Experimental design and procedure

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

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

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

2.5 Data collection and processing

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

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

- **Time headway (THW) in car-following** was calculated as the distance between ego and lead vehicle plus the length of lead vehicle (headway) [m] divided by the speed of the ego vehicle [m/s] (see Figure 2(a)). The car-following event was considered five seconds after the moment when the participant changed lane and ended five seconds before the next lane change. This is to exclude those moments just before a lane change when the driver may get closer to the lead vehicle as a preparation for the lane change, or just after a lane change until the driver adjusts the gap to the car-following situation. In addition, to differentiate the car-following and free flow driving, car-following was defined as when the ego vehicle is following a lead vehicle with THW equal or less than 3s [23][24].

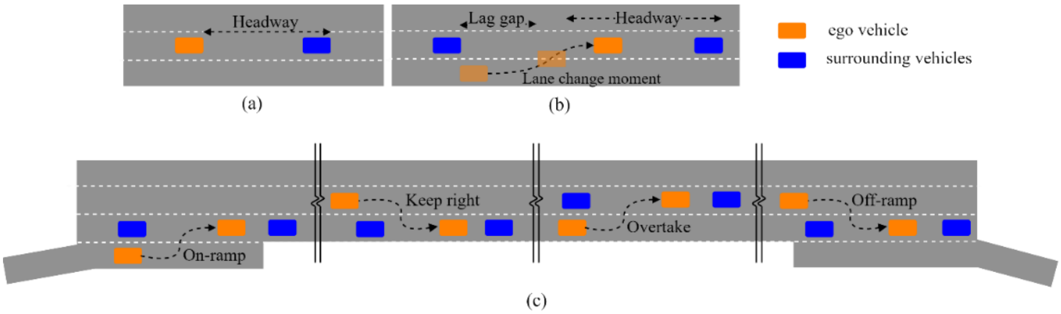

Figure 2: (a) Car-following and (b) lane changing parameters, (c) different lane change types.

- **Time gap in lane changing** was calculated as the sum of headway [m] divided by the speed of the ego vehicle and distance between ego and lag vehicle (lag gap) [m] divided by the speed of the lag vehicle [m/s]. A lane change gap is calculated the moment when the center of the ego vehicle passes the lane marking (see Figure 2(b)). Four types of lane changes were defined (Figure 2(c)):
- **On-ramp**: when the ego vehicle accepts a gap to enter the slow lane from the on-ramp (acceleration lane). In total there were 4 on-ramps in every scenario. The first one was excluded from the analysis since it happened at the beginning of the scenario without being next to any traffic.
- **Off-ramp**: when the ego vehicle accepts a gap in order to change lane from the middle lane to the slow lane to enter the off-ramp (deceleration lane) to exit a section of the highway. This type of lane change happened when the deceleration lane is available, and the participant has already seen the road sign showing the destination. In total there were 3 off-ramps in every scenario. However, those participants who kept driving on the slow lane did not have to accept any gap when changing lane to the deceleration lane. As a result, only 45 out of 51 participants have off-ramp gap measurements.
- **Keep right**: when the ego vehicle changes lane to the slow lane after he/she has completed an overtake.
- **Overtake**: when the ego vehicle changes lane to the fast lane for an overtake.

It should be noted that, a limitation of 75m for the longitudinal distance for lane change gaps were considered for inclusion in the analysis. This is suggested by Yang et al. to determine that the ego vehicle has interaction with the lead vehicle [25]. We considered this limitation for both lead and lag gaps. This way total merging gaps will be limited to maximum150m or around 6 seconds.

3. Analysis and Results

This section presents the results of the Linear Mixed Effects Models (LMM) which were conducted to compare the THWs and merging gaps considering the different scenarios and participants' demographics.

3.1 Linear Mixed Effects Models (LMM)

To test the research expectations, Linear Mixed Effects Models (LMM) were estimated to compare the THWs and merging gaps across the different scenarios, taking into account the participants' demographics.

The LMM is a widely used method to analyze unbalanced longitudinal data, where individuals may be measured at different time points, or at even different number of time points. LMMs are able to consider random effects that cannot be controlled for in the experiment. Random effect models have been widely utilized for this purpose [26][27][28].

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

In total, five LMMs (car-following THW, critical THW, on-ramp accepted gaps, off-ramp accepted gaps, and keep right accepted gaps) were developed, as shown in Table 1Table ***3***. The THW$\leq$ 1.5s was chosen as the critical THW because in practice, the average THW during the capacity conditions of a Dutch freeway is approximately equal to 1.5s, which represents a capacity of 2.400 veh/hr/lane [29]. Backward elimination method was used for the selection of variables. First the full independent variables were included in the model, then the most insignificant ones were eliminated until reaching a set of variables that all have a significant influence on the model.

3.2 Car-following behavior

In order to compare the car-following behavior in different scenarios, LMMs were developed considering the THWs equal or smaller than 3s to exclude the free-flow condition as mentioned earlier. The LMMs were performed in two ways: Model (a) only considering the main independent variables without any interactions. Model (b) considering the main independent variables with possible interactions which appeared to be significant in the model. The reason for presenting both models is that when including too many interactions of a variable in the model, that variable (scenario in our case) will not be significant, although it is so without considering the interactions.

Table 1: Linear Mixed Effects Model for car-following (THW≤ 3s)

		Model (a)			Model (b)		
Variables		**Coefficient**	**p-value**	**Z**	**Coefficient**	**p-value**	**Z**
Intercept		1.337	<0.001	7.047	1.304	<0.001	6.805
Scenario	DL (vs. Base)	-0.128	0.029	-2.187	Not significant in the model		
	Mix (vs. Base)	Not significant in the model			Not significant in the model		
Gender	Female (vs. Male)	0.158	0.061	1.871	0.157	0.062	1.866
Lane	Middle (vs. Slow)	0.056	<0.001	37.776	0.012	<0.001	5.217
Age		0.048	0.003	3.015	0.060	0.001	3.356
Education		0.086	0.033	2.130	0.088	0.029	2.180
Lane * Scenario	Middle (vs. Slow), DL (vs. Base)				-0.058	<0.001	-17.141
	Middle (vs. Slow), Mixed (vs. Base)				0.249	<0.001	66.543
Age * Scenario	Middle (vs. Slow), DL (vs. Base)				-0.033	0.084	-1.730
	Middle (vs. Slow), Mixed (vs. Base)				Not significant in the model		
Statistics							
Number of observations				748866			748866
Number of groups				51			51
Log-likelihood				-536450.24			-532901.10
AIC				1072912.48			1065818.20
BIC				1072981.64			1065910.41

As it is shown in Table 1, Model (a), in the DL scenario, the participants drove with considerably smaller THWs (0.128s smaller), compared to the other two scenarios. The results also indicate that younger, male drivers kept smaller THWs in general compared to older female drivers. Finally, drivers with higher education kept larger THWs in general.

Considering Table 1, Model (b), although the THW is shown to be larger on the middle lane in general (0.012s larger), when considering the interaction between the lane and scenario, the results reveal that THW is significantly smaller in DL scenario and on the middle lane when the participants drove right next to the CAV platoons on the dedicated lane (0.058s smaller). It should be mentioned that the THWs on the fast lane are not included in LMM analysis since drivers rarely used this lane in Base and Mixed scenario and were not allowed to drive on it in DL scenario. Considering gender and education, we can see the same trend as explained in Model (a). Moreover, interesting results were found regarding age. Model (b) indicated that older drivers keep significantly larger THWs. However, when considering the interaction between age and scenario, it is found that older drivers decrease their car following THW in DL scenario compared to Base (significant at the 10% level), while this has not happened in Mixed scenario. It can be concluded that, older drivers are more likely to adapt their behavior when driving next to platoons compared to young people.

Next, LMMs were developed for critical car-following behavior considering THWs equal or smaller than 1.5s. Table 2, Model (c) and Model (d) show the results of LMM without and with interactions, respectively. Similar to Model (a) shown in Table 1, Model (c) reveals that drivers drive significantly closer to their leaders in DL scenario compared to Base (0.042s smaller). However, the coefficient indicates that this decrease in critical THW is not as high as the decrease in car-following THW (0.128s) in Model (a).

In line with the results of the car-following behavior in Table 1, older drivers and drivers with high education increased their critical THW relative to their leaders. Considering Model (d) including the interactions, it can be seen that drivers decreased their critical THWs on the middle lane in both DL and Mixed scenario. However, the decrease in DL scenario is more than four times larger than in Mixed scenario (0.046s and 0.011s decrease in DL and Mixed respectively).

Table 2: Linear Mixed Effects Model for critical car-following (THW≤ 1.5s)

		Model (c)			Model (d)		
Variables		**Coefficient**	**p-value**	**Z**	**Coefficient**	**p-value**	**Z**
Intercept		1.029	<0.001	17.284	1.020	<0.001	17.038
Scenario	DL (vs. Base)	-0.042	0.038	-2.072	Not significant in the model		
	Mixed (vs. Base)	Not significant in the model			Not significant in the model		
Age		0.016	0.003	2.979	0.017	0.003	3.013
Education		0.044	0.001	3.291	0.044	0.001	3.259
Lane	Middle (vs. Slow)				0.023	<0.001	15.319
Lane * Scenario	Middle (vs. Slow), DL (vs. Base)				-0.046	<0.001	-22.875
	Middle (vs. Slow), Mixed (vs. Base)				-0.011	<0.001	-4.625
Statistics							
Number of observations				285542			285542
Number of groups				51			51
Log-likelihood				110241.43			110523.29
AIC				-220472.86			-221034.58
BIC				-220420.05			-220971.21

3.3 Lane change behavior

Three LMMs were also estimated to compare the lane change accepted gaps between the different scenarios. Table 3 illustrates that off-ramp and on-ramp accepted gaps were significantly shorter in DL compared to Base scenario. In terms of keep right lane changes, scenario turned out to be a significant factor once again. Table 3 indicates that keep right gaps were decreased in Mixed and DL scenario compared to Base. However, the coefficient shows that this decrease is greater in DL compared to Mixed scenario.

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

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

		Off-ramp			On-ramp			Keep right		
Variables		**Coef.**	**p-value**	**Z**	**Coef.**	**p-value**	**Z**	**Coef.**	**p-value**	**Z**
Intercept		3.524	<0.001	28.941	4.019	<0.001	39.469	3.961	<0.001	29.437
Scenario	DL (vs. Base)	-0.383	0.026	-2.230	-0.578	<0.001	-4.068	-0.431	0.028	-2.199
	Mix (vs. Base)	Not significant in the model			Not significant in the model			-0.361	0.026	-2.223
Statistics										
Number of observations				181			300			194
Number of groups				45			51			45
Log-likelihood				-254.28			-416.77			-263.00
AIC				512.56			837.54			530.00
BIC				518.96			844.95			536.54

4. Discussion

4.1 Behavioral adaptation in Mixed situation:

The first expectation was that behavioral adaptation would be negligible in a mixed traffic of CAVs and MVs at moderate PRs. One of the scenarios in the experiment was to drive on a freeway with mixed traffic of MVs and CAVs while the PR of CAVs was 43% (Mixed scenario). The objective was to compare the car-following and critical THWs (THW $\leq$ 3s and THW $\leq$ 1.5s respectively) and lane change gaps in Mixed scenario with Base scenario with the same traffic flow per lane in each scenario. LMM compared the THWs in both situations and revealed that there is no significant difference in car-following THWs between the two scenarios. This shows that the few number of platoons, which were scarce on the freeway, did not influence the car-following behavior of MV drivers. Regarding the lane change gaps, the comparison of Base and Mixed scenario showed that no significant changes happened in on-ramp and off-ramp gaps when driving next to few platoons for a short time.
In fact the exposure time (the time when the ego vehicle was driving next to a platoon) was too short to influence the behavior of MV drivers [6]. Moreover, in the current experiment the number of platoons and the platoon size were kept very low to represent the PR of 43%. So, the conspicuity of the platoons was not high enough to influence the car-following and lane changing behavior of MV drivers. This supports the conclusions obtained by Gouy et al. [6] which indicated that exposure time and conspicuity of platoons are important factors in behavioral adaptation of MV drivers. They also indicated that there was no carry over effect in behavioral adaptation from the situation when car-following happened next to platoons keeping short THW (0.3s) to long THW (1.4s). This supports the fact that driving next to a platoon for a few seconds cannot influence the car-following behavior for the entire drive.
On the other hand, considering the keep right maneuvers, LMM revealed that merging gaps decreased significantly in Mixed scenario (9%) compared to Base. Keep right gaps were not significantly different between DL and Mixed scenario. However, because Base was always the first scenario to drive, the participants might have gotten used to the simulator environment and feel more comfortable to accept shorter gaps when they drove in Mixed and DL scenarios.

4.2 Behavioral adaptation when driving next to dedicated lanes:

The second expectation stated that with concentrating CAV platoons on one lane (the DL), the car-following THWs (Expectation 2a) and lane change gaps (Expectation 2b) will decrease significantly due to behavioral adaptation. To test this expectation, participants were asked to drive on a freeway with one dedicated lane to CAV platoons. The comparison between Base and DL scenario showed that MV drivers significantly decreased their car-following THW (7%) and critical THW (3.5%) in DL scenario, especially when they were driving on the lane adjacent to DL where platoons drive. In fact, when platoons were concentrated on one lane, their exposure time and conspicuity was increased to the extent that it influenced the car-following behavior of MV drivers. This is in line with the results of previous experiment when participants were asked to drive next to continuous access DL and limited access DL with buffer [7]. This also confirms the other two experiments of Gouy et al. with no dedicated lane [5][6]. Although there was no dedicated lane proposed in those experiments, the fast lane of the freeway was in practice used as a dedicated lane since all CAVs were driving on that lane.
It has been concluded from a previous study that MV drivers tend to show more “radical behavior” by greater steering magnitude and steering velocity when they change lanes into a CAV lane [30]. Similarly, in this study, it appeared that MV drivers accept shorter gaps when changing lane for on-ramps, off-ramps and keep right maneuvers (Expectation 2b confirmed). Given that the traffic flows were equal per lane for all scenarios, accepting smaller gaps could be a result of imitating the behavior of CAVs and is unlikely to be affected by the offered gaps in traffic.

4.3 Behavioral adaptation and the impacts of demographics:

Expectation 3 indicated that participants’ demographics play important roles in behavioral adaptation in car-following and lane changing. The results of LMM for car-following THW showed that male drivers follow their leaders keeping smaller THWs (9%). This is in line with the results from the literature which revealed a positive correlation between being a male driver and close car-following and shorter gap-acceptance in lane changing [19][20]. However, gender impact was not seen in critical THWs.
Furthermore, driver education turned out to be a significant predictor in car-following behavior. Drivers with high education followed their leaders with larger THWs in all scenarios and did not adapt their car-following behavior in DL scenario even when they drove on the lane adjacent to CAV platoons. This can be explained by the fact that people with higher education usually are more aware of the new technologies and may be more familiar with CAV behavior and can distinguish the difference between CAVs and own capabilities in relation to close car-following. Moreover, some of the participants with higher education who participated in the experiment were students of the same department who worked directly in the fields related to CAVs.

Finally, younger drivers kept smaller THWs in car-following. This is in line with the findings of Rajalin et al. which showed that younger drivers tend to follow their leader more closely [19]. Moreover, examining the interaction between age and scenario revealed that older drivers adapt their behavior more than younger ones when driving on a highway with a dedicated lane to CAV platoons. This was shown by a significant decrease in car-following THW in DL scenario compared to the other two scenarios. However, this decrease was not seen in critical THW which shows that unwanted behavioral adaptation may occur to older drivers in car-following but not to the extend which leads to risky behavior (at least at moderate PRs of CAVs). Thus research on the impacts of age on behavioral adaptation is recommended to further support these results.

5. Conclusion

This study investigated the behavioral adaptation of drivers of MVs in car-following and lane changing when driving in a mixed traffic with CAV platoons as well as driving on separate lanes but adjacent to the CAV dedicated lane at a moderate PR (43%). Based on the results, MV drivers are not likely to adapt their behavior in car-following and lane changing in mixed traffic situation at moderate PR of CAVs. However, at the same PR, implementing a DL would increase the density of CAVs on one lane and consequently increases the exposure time and conspicuity of CAV platoons. So, MV drivers could see the CAV platoons keeping very short THWs more often. We provide evidence that this leads to a situation where MV drivers tend to imitate the behavior of CAV platoons by following a lead car more closely and accepting shorter gaps in lane changing.
Behavioral adaptation is not necessarily considered negative as long as it is not leading to risky maneuvers which a human driver is not able to control. In fact, adopting shorter THWs (in manageable range by a human) in car-following could increase the capacity of a freeway. So, if MVs are equipped with systems such as collision avoidance to avoid close car-following by the time we accommodate CAV platoons on our road network, risky maneuvers can be avoided. However, it requires time and budget to replace the entire vehicle fleet with new ones. This way we can avoid the potential unsafe consequences of behavioral adaptation and exploit the smoothness of the traffic flow generated by CAVs.
This study further gave insights regarding the impacts of demographics of MV drivers on their behavioral adaptation. Age, gender, and education turned out to be significant factors in car-following as expected based on literature. It was observed that older drivers are more prone to behavioral adaptation in car-following but not to the extend which leads to critical or risky behavior. Moreover, drivers with higher education showed no behavioral adaptation when driving next to CAV platoons. This could be because of their higher information regarding CAV technology. Therefore, it would also be important to investigate whether human drivers still imitate the behavior of CAVs after they are educated about the differences between human driver and CAV capabilities.
Due to both technical and ethical reasons, it was not possible to perform a field test, therefore, a virtual reality environment was used to investigate the study research expectations. This brings along questions regarding real-world behavioral adaptation of MV drivers. Therefore, future pilot field tests would be needed to validate the results. Moreover, behavioral adaptation was measured over a limited time and at only one PR (43%). Thus, future research is needed on the long-term effects of behavioral adaptation and at different PRs.

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