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Behavioral adaptation of drivers when driving among automated vehicles

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Abstract

Purpose – This paper aims to explore whether drivers would adapt their behavior when they drive among automated vehicles (AVs) compared to driving among manually driven vehicles (MVs).Understanding behavioral adaptation of drivers when they encounter AVs is crucial for assessing impacts of AVs in mixed-traffic situations. Here, mixed-traffic situations refer to situations where AVs share the roads with existing nonautomated vehicles such as conventional MVs.

Design/methodology/approach – A driving simulator study is designed to explore whether such behavioral adaptations exist. Two different driving scenarios were explored on a three-lane highway: driving on the main highway and merging from an on-ramp. For this study, 18 research participants were recruited.

Findings – Behavioral adaptation can be observed in terms of car-following speed, car-following time gap, number of lane change and overall driving speed. The adaptations are dependent on the driving scenario and whether the surrounding traffic was AVs or MVs. Although significant differences in behavior were found in more than 90% of the research participants, they adapted their behavior differently, and thus, magnitude of the behavioral adaptation remains unclear.

Originality/value – The observed behavioral adaptations in this paper were dependent on the driving scenario rather than the time gap between surrounding vehicles. This finding differs from previous studies, which have shown that drivers tend to adapt their behaviors with respect to the surrounding vehicles. Furthermore, the surrounding vehicles in this study are more "free flow'" compared to previous studies with a fixed formation such as platoons. Nevertheless, long-term observations are required to further support this claim.

Keywords Automated vehicles, Driver behaviors and assistance, Human–robot interaction, Behavioral adaptation, Driving simulator experiment

Paper type Research paper

1. Introduction

In the transition to traffic with fully autonomous vehicles, the early phase of automated vehicles (AVs) deployment on public roads is a crucial phase. This phase is where AVs will share the roads with existing nonautomated vehicles such as conventional manually driven vehicles (MVs). Studies, e.g. in Andreotti *et al.* (2020), Ngoduy (2015), Yang *et al.* (2014), Morando *et al.* (2018), have shown that AVs could potentially affect transportation systems in many ways in such mixed traffic condition (mixture between AVs and MVs).

Since the introduction of advanced driver assistance systems (ADAS), many studies have suggested that behavior adaptation can be observed in drivers who interact with ADAS or automated driving systems (ADS), or those who operate AVs and connected vehicles (Sullivan *et al.*, 2016; Hiraoka *et al.*, 2010; Robertson *et al.*, 2017; Varotto *et al.*, 2020; Ali *et al.*, 2021). However, how these new systems would influence behavior of other road users was not thoroughly studied until recently (Gouy *et al.*, 2014; Schoenmakers *et al.*, 2021; Soni, 2020). It is still unclear how and whether drivers today would adapt their behavior when they encounter or interact with AVs on public roads.

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1.1 Behavioral adaptation

Following the definition suggested by Rämä and Kulmala (2013): behavioral adaptation can be defined as "any change of driver, traveller and travel behaviours that occurs following user interaction with a change to the road traffic system, in addition to those behaviours specifically and immediately targeted by the initiators of the change."

Behavioral adaptation can be experienced by users of ADAS, ADS or AVs (i.e. drivers who themselves are exposed to using the [assistance] systems or AVs), as reported in several studies, Sullivan *et al.* (2016), Hiraoka *et al.* (2010), Robertson *et al.* (2017), Varotto *et al.* (2020), Louw *et al.* (2020), Metz *et al.* (2020) and Sibi *et al.* (2020).

In this paper, we focus on behavioral adaptation by drivers of MVs who have been driving near or in the surrounding of AVs. For example, in a simulator study (Gouy *et al.*, 2014), where research participants were asked to drive following a lead vehicle while AV platoons were presented in an adjacent lane. Their results suggested that time headway (THW) of the AV platoons has influence on the participants' THW; i.e. participants were found to keep significantly shorter THW when THW for the platoon was short (0.3 s) compared to when the THW for the platoon was longer (1.4 s).

Another simulation study (Schoenmakers *et al.*, 2021) examined behavioral adaptation where three different types of a dedicated lane for AVs were introduced. They asked research participants to drive next to AVs in the different dedicated lanes on motorways. They observed a significant reduction of THW in the presence of AVs with different magnitudes depending on the road design.

Unlike Gouy *et al.* (2014), Schoenmakers *et al.* (2021) who studied behavioral adaptation from simulation studies, (Soni, 2020) analyzed data from a field test that was designed to study if drivers of MVs experience behavioral adaptation related to gap acceptance, car following and overtaking behavior after interaction with AVs. The author found that the drivers accepted significantly lower critical gaps during interactions with AVs compared to during interactions with other MVs. In terms of car-following and overtaking behaviors, no significant differences were found when the participants interact with other MVs or with AVs. Further, the author's analysis also suggested that, after an increased number of interactions with AVs, the participants adopted a significantly lower headway at the end of overtaking during interaction with AVs.

1.2 Objective of this study

The objective of this study is to investigate if and how human drivers adapt their driving behavior while driving among AVs in two different driving scenarios, namely, *main highway* and *on-ramp* scenarios. Each scenario is repeated twice, each with all surrounding vehicles being either MVs or AVs. Eighteen research participants were recruited for this driving simulation study, which explores behavior adaptation under the two scenarios with different surrounding traffics.

Compared to previous work, our study investigates behavior adaptation in a more "free flow" condition. In other words, we do not control the behavior or formation of AVs during our experiments and let the AVs freely regulate themselves in the traffic.

1.3 Outline of this paper

The remaining part of this paper is structured as follows. Section 2 presents experimental setup of this study. Specific details with regard to modeling of AVs and MVs are presented in Section 3. Section 4 presents results collected from the 18 research participants. The paper then discusses limitation of this study in Section 5 along with suggestions for future work. Finally, Section 6 concludes the paper.

2. Experimental setup

Experiments in this study were conducted at the facility of the Swedish National Road and Transport Research Institute (VTI) in Gothenburg, Sweden. An ethical approval for this study has been obtained from the Swedish Ethical Review Authority (dnr 2020–05801); the council concluded that the study does not fall into scope of the Swedish Ethical Review Act (SFS 2003:460) and thus shall not be ethically tested.

2.1 Participants

We have recruited a total of 18 research participants, who have registered their interest to participate in driving simulation studies in VTI's database. Ten male and eight female were invited to participate in this study. The average age of this group is about 44 years old (the youngest and the oldest participants are 23 and 65 years old, respectively). Selection criteria were to select drivers above 18 years old, who drive more than 5,000 km per year.

2.2 Procedure

When a participant arrives, a brief information about the procedures and experiments was provided. The consent form was then given to the participant to ask for his/her approval. After the participant signed the consent form, he/she was asked to fill in another form to collect personal information such as age, gender and driving experiences. This was then followed by more information about the experiment; the participant was told that he/she will experience two different types of surrounding vehicles: MVs (represented as black cars) and AVs (represented as red cars).

The participant was then seated inside the passenger car cabin (see Figure 2), and the test leader introduced how to use the simulator. To familiarize the participant with the simulator, a driving simulation experiment starts with about 3 min of a training session on a road without any surrounding traffic. After the training, the participant experienced four different scenarios on the same road with either different type of traffic or starting position on the road (see Section 2.3).

When the simulation runs concluded, a questionnaire was given to the participant. The questionnaire asked the participant to "Mark a cross (X) in the box that you think best matches how you experience the autonomous vehicles" followed by the acceptance scale proposed in Van Der Laan *et al.* (1997). All documents and questionnaires given to the participant were available both in English and Swedish languages. Finally, a short interview was conducted with three main objectives:

1. find out whether the participants believe that they behaved differently;

2 find out whether they observe any differences in different traffics; and
3 to collect other feedback from the participants regarding the experiments.

2.3 Scenario

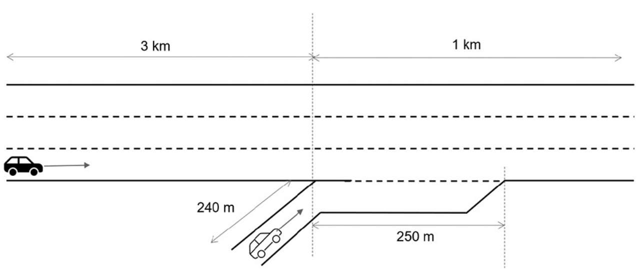
As mentioned above, four different scenarios were presented to the participants in this study. Each participant experienced the scenarios in a unique predefined order generated according to the balanced Latin Square method (Latin Square Designs, 2008) to minimize order effects. Order effects refer to situations when order of the conditions, which are presented to research participant, may have effect on results. Starting position on the road and types of surrounding traffic are varied in different scenarios, which occur on the same road geometry (see Figure 1). The four different scenarios and their conditions are summarized in Table 1.

The surrounding traffic in each scenario is either all MVs or all AVs. All vehicles (both ego and surrounding) in the scenarios start at a standstill (0 km/h). Once the research participants start moving the ego vehicle, traffic are systematically generated to surround the ego vehicle by inserting vehicles ahead and behind the ego vehicle. The simulation ensures that there are always maximum ten vehicles inside 500 meters radius around the ego vehicle. Moreover, in the *main highway* scenario, the research participants begin the scenario with four vehicles already surrounding the ego vehicle. One vehicle was always inserted to the on-ramp when the ego vehicle approaches the merging section during the *main highway* scenario. Speed limit of the road is set to 90 km/h (25 m/s).

2.4 Simulation tool

This study was conducted using the "SimIV" moving-based driving simulator with passenger car cabin as a driving interface; please refer to Jansson *et al.* (2014) for more details about the *SimIV*. The passenger car cabin are depicted in Figure 2. The main driving simulation software used in the simulator is developed in-house at VTI. However, Simulation of Urban Mobility (SUMO) (Lopez *et al.*, 2018) is coupled with the driving simulation software to generate surrounding traffic in the test scenario. A connection between SUMO and the driving simulation software was made based on the approach used in a previous work (Aramrattana *et al.*, 2019).

Figure 1 Geometry of the road used in this study



Note: Depending on the scenario, there are two possible starting points indicated with black and white cars

Table 1 List of four different experimental scenarios with their respective conditions

ID	Starting position	Surrounding traffic
RAMP-MV	On-ramp (white car in Figure 1)	All MVs
MAIN-MV	Main highway (black car in Figure 1)	All MVs
RAMP-AV	On-ramp	All AVs
MAIN-AV	Main highway	All AVs

2.5 Data collection

Apart from driving behavior of the research participants, position and speed of surrounding vehicles (if any) within the range of 100 meters ahead and behind the ego vehicle were also collected. An example of these surrounding vehicles is depicted in Figure 3 (Table 2).

3. Modeling of surrounding traffic

As mentioned above, surrounding traffic is generated using SUMO. Two different car-following models were used in this study to represent MVs and AVs.

3.1 Manually driven vehicles

Car-following behavior of MVs is modeled using a modified version of the *intelligent driver model (IDM)* (Treiber *et al.*, 2000), which is implemented in SUMO (SUMO version 1.3.1 is used in this study). Modifications were done to represent specific car-following behavior between cars. The modified version will be referred to as *H-IDM* car-following model

Figure 2 Passenger car cabin of the "SimIV" driving simulator

Figure 3 Surrounding vehicles (white) around the ego vehicle (black)

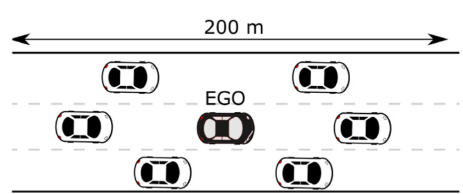


Table 2 Summary of H-IDM performance compared to the HighD data set (t_{gap} indicates time gap during car-following period)

	HighD	H-IDM	Difference
Median of t_{gap} (s)	1.43	1.40	0.03
Mean of average follow speed (m/s)	30.06	28.58	1.48
Number of lane change	2,647	2,218	429

(heterogeneous IDM car-following model). For H-IDM model, an additional parameter for representing minimum desired THW (tau_{CC}) was added to regulate car-following distance between cars. H-IDM uses the tau_{CC} parameter only for longitudinal car-following behavior; the original *tau* in SUMO is still used for lane changing decisions.

Final parameters for H-IDM are presented in Table 3. Behavior of the H-IDM car-following model with the final parameters in SUMO simulation compared to the HighD data set is presented in Table 2. Values of the presented performance indicators are aggregated over simulations of all ten selected data sets, and compared with their respective values extracted from the ten data sets. The results suggest that the behavior of H-IDM is similar to characteristics of vehicles observed in real traffic situations, in terms of car-following and lane-changing behaviors.

3.2 Automated vehicles

AVs are modeled according to the parameter set suggested by the TransAID project (Mintsis *et al.*, 2019), which is implemented as the *ACC* car-following model in SUMO.

Table 3 presents parameters used for both AVs and MVs in SUMO. Names of the parameters are according to SUMO User Documentation (see https://sumo.dlr.de/docs/Definition_of_Vehicles%2C_Vehicle_Types%2C_and_Routes.html [accessed 16 July 2022] for further details).

Table 3 Attributes of vehicles in SUMO simulation (naming are according to SUMO's documentation; default values are used for attributes not listed below)

Parameters	MVs	AVs
accel (m/s^2)	2.9	2.9
decel (m/s^2)	−7.5	−7.5
emergencyDecel (m/s^2)	−9.0	−9.0
length (m)	5	5
minGap (m)	0.5	0.5
maxSpeed (m/s)	70	70
speedFactor	1.1	1.0
speedDev	0.2	0.0
vClass	Passenger	Passenger
Car-following model	H-IDM	ACC
– tau	1.2	1.6
– tau_{CC}*	1.0	–
Lane-changing model	LC2013	LC2013
– lcAssertive	3.0	0.7
– lcSpeedGain	2.5	1.0

Note: *tau_{CC} is a special parameter for H-IDM and not a standard SUMO parameter (see Section 3.1)

4. Results

Four indicators are selected to represent driving behaviors in this study:

1. average time gap during car-following (t_{gap});
2. average total number of lane change(s) (LC);
3. average overall speed [1] ($\overline{v}$); and
4. average speed during car-following ($\overline{v}_f$).

We consider two vehicles to be following each other when the time gap between them is less than 6 s [2], and thus, this criteria is used to obtain t_{gap} and $\overline{v}_f$ listed above.

4.1 Baseline behavior

To establish baseline behaviors for AVs and MVs, the AVs and MVs were simulated in SUMO on the road depicted in Figure 1. All scenarios described in Table 1 were simulated, with an *ego vehicle* starting at the same position as research participants (the ego vehicle was assumed to be the same type with the surrounding traffic). Other surrounding vehicles are generated in the same way as in the driving simulation experiment. Similar to the driving simulation experiment, note that all vehicles start at a standstill (0 km/h) and that there are maximum ten vehicles surrounding the ego vehicle within a 500-meter radius.

Behaviors of the simulated AVs and MVs with respect to the indicators listed above are summarized in Table 4. According to Table 4, comparing scenarios with all MVs (RAMP-MV and MAIN-MV) with all AVs (RAMP-AV and MAIN-AV), we can observe that MVs change lane more frequently than AVs and have a higher average speed. In the scenario RAMP-AV, t_{gap} for the ego vehicle is stated as not available (n/a) because the ego vehicle did not follow any vehicle during the simulation. In this case, the ego vehicle waits for the traffic to pass at the on-ramp before merging on to the main road.

4.2 Research participants' behavior

This section presents results from the 18 research participants in the driving simulation study conducted according to the description in Section 2 using surrounding traffic as modeled in Section 3.

Overall driving behaviors of the research participants and surrounding vehicles (according to criteria in Figure 3) are summarized in Table 5. During the *on-ramp* scenarios (scenario RAMP-MV and RAMP-AV), the average t_{gap} is reduced from 2.3 to 1.3 s when the participants drove among AVs. On the other hand, the average t_{gap} increases from 3.0 to 3.5 s when the participant drove among AVs in the *main highway* scenario (scenario MAIN-MV and MAIN-AV). The average of overall speed ($\overline{v}$) follows the same trend for both scenarios, but the participants' average car-following speed ($\overline{v}_f$) is reduced for both scenarios. Last but not least, we can observe that the participants change lanes less frequently when driving among AVs.

Most of these adaptations follow characteristics of the surrounding vehicles, where the AVs have lower overall speed and higher time gap. However, the opposite can be observed for the time gap during the *on-ramp* scenario.

Furthermore, for each participant, we individually compared differences in the distribution of t_{gap}, $\overline{v}$ and $\overline{v}_f$. Each parameter is compared between driving among AVs and MVs under the same scenario (i.e. RAMP-MV vs RAMP-AV and MAIN-MV

Table 4 Behavior of vehicles in SUMO simulation

ID	Baseline ego vehicle t_{gap} (s)	LC (n)	$\overline{v}$ (m/s)	$\overline{v}_f$ (m/s)	Baseline surrounding vehicles t_{gap} (s)	LC (n)	$\overline{v}$ (m/s)	$\overline{v}_f$ (m/s)
RAMP-MV	1.7	1	24.60	27.19	1.7	13	26.53	25.93
MAIN-MV	1.8	3	27.12	24.03	3.0	25	25.64	24.68
RAMP-AV	n/a	1	18.62	n/a	2.6	6	22.88	23.26
MAIN-AV	2.6	1	23.56	24.07	3.0	9	24.04	24.78

Table 5 Overall driving behaviors of research participants and surrounding vehicles (see Figure 3)

ID	All research participants t_{gap} (s)	LC (n)	$\overline{v}$ (m/s)	$\overline{v}_f$ (m/s)	Surrounding vehicles t_{gap} (s)	LC (n)	$\overline{v}$ (m/s)	$\overline{v}_f$ (m/s)
RAMP-MV	2.3	1.7	20.18	24.93	2.9	n/a	27.02	24.55
MAIN-MV	3.0	2.5	23.63	24.09	2.6	n/a	24.13	23.75
RAMP-AV	1.3	1.2	19.72	23.99	3.3	n/a	23.80	23.02
MAIN-AV	3.5	1.3	23.29	23.79	2.9	n/a	22.82	24.19

vs MAIN-AV). The parameters were tested using Wilcoxon sign-ranked test (the Wilcoxon test is chosen because the datasets are not normally distributed). Out of all pair-wise comparisons, significant differences in distribution are found for most comparisons: 34/36, 35/36, 33/36 for t_{gap}, $\overline{v}$ and $\overline{v}_f$, respectively (tests were done with 99% confidence interval; $\alpha = 0.01$).

Although it is evident that the participants changed their behavior, magnitudes of the observed changes were not unanimous; i.e. some participants increased their t_{gap} when driving among AVs compared to MVs, while others decreased their t_{gap}. These observations suggest that changes in behavior are also dependent on the driving scenario. For instance, overall t_{gap} is lower in AV traffic compared to the MV traffic during the *on-ramp* scenario (scenario RAMP-MV vs RAMP-AV), but the overall t_{gap} is higher in AV traffic compared to the MV traffic in the *main highway* scenario (scenario MAIN-MV vs MAIN-AV). Nevertheless, we observe adaptations in both directions in all driving scenarios and traffic types.

Last but not least, results from the acceptance questionnaire given to the participants after the experiment were processed according to Van Der Laan *et al.* (1997). The results suggest that the participants generally have positive opinions about the AVs with average usefulness score of 0.86 and satisfaction score of 0.54 (the scale is between −2 and 2). As suggested in Van Der Laan *et al.* (1997), reliability of the answers was measured using Cronbach's alpha, which are 0.82 and 0.86 for usefulness and satisfaction, respectively. The alpha values are considered sufficiently high if they are greater than 0.65 (Van Der Laan *et al.*, 1997). The participants' opinion can be one of the factors that determined the behavior adaptation.

In summary, behavior adaptation can be observed from both individual and overall driving behavior, and thus, this suggests that the participants adapt their driving behavior when presented with different behaviors of vehicles in their surroundings. The overall manner of their adaptations, i.e. how much the participants adapt, is dependent on the driving scenario and not necessarily following the characteristics of the surrounding traffic. When comparing each indicator among the participants, adaptation can be observed in both directions in all scenarios. Therefore, we cannot clearly conclude how drivers would adapt their behavior when they encounter AVs.

5. Discussions and future work

One of the limitations of this study is that duration of the scenarios is short. It takes about 3 min to complete the main highway scenario, and the on-ramp is even shorter (usually about 1 min). This limitation is also recognized and raised by many of the participants in this study during the post-experiment interview. Therefore, duration of the experiment shall be increased in the future work. Increasing the duration would allow us to observe the driving behavior over a longer period of time, which could provide more insights.

In this study, all vehicles in the surrounding traffic are either MVs or AVs, meaning that there is no mixture between these vehicle types for the surrounding traffic. This can be seen as another limitation of this study. Therefore, a future work, where surrounding vehicles are different mixtures of AVs and MVs would be valuable. Due to short driving scenarios as discussed above, we limit the traffic types to all AVs or MVs, as we would like to guarantee that we always have data of each participant interacting with both vehicle types. Having a mixture of traffic would not ensure that the participants spend equal time driving among AVs and MVs.

AVs in our study exhibit a relatively defensive behavior, where they generally kept a longer time gap than MVs and have less variation in speed. This particular model is selected because it has been calibrated with real data through a few iterations. In the future work, other models of AVs shall also be considered, especially the alternatives that assume that AVs would be able to achieve a shorter time gap during car-following due to a shorter reaction time compared to MVs. Moreover, an improved model or a different model for MVs shall be considered in the future work.

Although AVs in our study tend to keep a longer time gap than MVs (see Tables 4 and 5), participants do not always adapt their behavior according to this characteristics, as can be seen in the overall behavior of the *on-ramp* scenario and individual analysis presented in Section 4. This finding is in line with the insight regarding car-following behavior in Soni (2020), where half of the participants were found to keep smaller THW to Avs, while the other half keep larger THW. However, this is in contrast to the general findings, Gouy *et al.* (2014) and Schoenmakers *et al.* (2021), that the drivers adapt their THW following the behavior of AVs. Therefore, further investigation in future work is required to understand such contrasts.

To this end, based on our observations, the participants selecting a shorter time gap for the RAMP-AV scenario, despite surrounding AVs having a longer time gap, could potentially be caused by the fact that AVs were more congested on the rightmost lane of the main highway and had a slower and more stable speed during the experiments, compared to MVs traffic which were faster and prefer faster lanes than the rightmost lane due to speed variation and more aggressive lane-changing parameters. These behaviors of AVs could potentially force the participants to merge onto the main highway between vehicles (and thus accepting a shorter time gap) rather than waiting for a vehicle to pass and merge later, where a larger space is available.

6. Conclusions

This paper presents results from a driving simulation study on potential behavior adaptation when drivers encounter AVs on the road. The study is set up as a with-in subject experiment, where all participants experienced all conditions. Two driving scenarios were studied: driving on a main highway and merging onto the highway from an on-ramp. The participants experienced each driving scenarios twice: once with all surrounding traffic being AVs and once with MVs.

Results from 18 research participants in this study suggest that behavior adaptation is dependent on both driving scenario and traffic characteristics. Moreover, our finding suggests that drivers do not always adapt their behavior following characteristics of the surrounding traffic. For instance, participants drove with a lower time gap, despite higher time gap between vehicles in the traffic. Furthermore, comparisons between AVs and MVs cases for each participant show that significant differences were found in terms of average time gap, number of lane changes, overall speed and car-following speed. Nevertheless, the observed magnitude of the changes were not unanimous (i.e. some had increased their speed, while the others had decreased it).

An investigation into a long-term effects would be crucial future work to better understand behavior adaptation, as this study explores the adaptation under a short period of time. Nevertheless, our study shows that such adaptation can already be observed in a short time period, and thus, this should be investigated further in future research.

Notes

1. We disregard data points, where speed is less than 1 m/s.
2. According to Vogel (2002), a driver chooses their speed independently when THW to the preceding vehicle is more than 6 s.

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