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Behavioral adaptations of human drivers interacting with automated vehicles

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ABSTRACT

Advancements in technology are bringing automated vehicles (AVs) closer to wider deployment. However, in the early phases of their deployment, AVs will coexist and frequently interact with human-driven vehicles (HDVs). These interactions might lead to changes in the driving behavior of HDVs. A field test was conducted in the Netherlands with 18 participants focusing on gap acceptance, car-following, and overtaking behaviors to understand such behavioral adaptations. The participants were asked to drive their vehicles in a controlled environment, interacting with an HDV and a Wizard of Oz AV. The effects of positive and negative information regarding AV behavior on the participants' driving behavior and their trust in AVs were also studied. The results show that human drivers adopted significantly smaller critical gaps when interacting with the approaching AV as compared to when interacting with the approaching HDV. Drivers also maintained a significantly shorter headway after overtaking the AV in comparison to overtaking the HDV. Positive information about the behavior of the AV led to closer interactions in comparison to HDVs. Additionally, drivers showed higher trust in the interacting AV when they were provided with positive information regarding the AV in comparison to scenarios where no information was provided. These findings suggest the potential exploitation of AV technology by HDV drivers.

1. Introduction

The topic of automated driving is currently in the limelight of researchers, policymakers, and vehicle manufacturers due to its potential benefits to road transportation, especially in terms of traffic flow and safety (Aria, Olstam, & Schwietering, 2016). These benefits result from the technological capabilities of AVs, such as the ability of platoon formation, shorter reaction times, shorter following headways, ability to continuously detect their surroundings, keeping track of all nearby road users, and smooth, stable, and predictable driving (Winkle, 2016). However, in the early phases of automation, mixed traffic will occur where both AVs and Human Driven Vehicles (HDVs) will coexist and interact.

Various studies that predicted the benefits of AVs implicitly assumed that human drivers would not change their driving behavior while interacting with AVs (Friedrich, 2016; Winkle, 2016). However, the recognisability of AVs due to their appearance might play a role in the behavioral adaptation of interacting human drivers (Fuest, Feierle, Schmidt, & Bengler, 2020). Since human drivers may

have mixed opinions and trust towards AVs, they might behave differently when interacting with an AV compared to when interacting with an HDV. The phenomenon of behavioral adaptation is defined as "unintended change in the behavior of the users with the introduction of a new system against the system's intended designed operation" (OECD, 1990). Behavioral adaptation generally focuses on the negative effects of the phenomenon as it may jeopardize the intended benefits of the system (Saad, 2004). Behavioral adaptation can appear in many different forms when driving, such as speed management (Melman, Abbink, Van Paassen, Boer, & De Winter, 2018), following distance, the way of overtaking or lane changing, braking, level of attention, and gap acceptance (Draskóczy, 1994).

A large number of studies have investigated how users of AVs take over control (Gold, Damböck, Lorenz, & Bengler, 2013; Varotto, Farah, Bogenberger, van Arem, & Hoogendoorn, 2020; Winter, Stanton, Price, & Mistry, 2016) and how vulnerable road users respond to AVs (Fuest, Michalowski, Schmidt, & Bengler, 2019; Palmeiro et al., 2018; Velasco, de Vries, Farah, van Arem, & Hagenzieker, 2021; Velasco, Farah, van Arem, & Hagenzieker, 2019). However, the behavioral adaptation of human drivers interacting with AVs, which is crucial to traffic safety and efficiency, has not been studied extensively yet. Some field tests and driving simulator studies have provided some evidence of behavioral adaptation of human drivers during their interaction with AVs (Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014; Rahmati, Khajeh Hosseini, Talebpour, Swain, & Nelson, 2019; Trende, Unni, Weber, Rieger, & Luedtke, 2019; Zhao et al., 2020). These studies are summarised in Table 1.

Car-following behavior has been studied more extensively than other types of driving behaviors. Few controlled field tests have been conducted to study one-on-one interactions between HDVs and AVs during car-following (Rahmati et al., 2019; Zhao et al., 2020). These studies found a reduction in headways while interacting with AVs, especially for drivers with higher trust in AVs. Similar findings were also observed in several driving simulator studies, where shorter headways were observed while driving near a platoon of automated vehicles (Gouy, 2013; Gouy et al., 2014; Schoenmakers, Yang, & Farah, 2021).

A few studies focused on the gap acceptance behavior of human drivers interacting with AVs. Trende et al. (2019) found in a driving simulator study that under time pressure drivers had a significantly higher gap acceptance probability at intersections when interacting with AVs compared to when interacting with HDVs. This suggests drivers' intentions to exploit the technological advantages of AVs and the AVs' ability to perform safer maneuvers. Rad, Farah, Taale, van Arem, & Hoogendoorn, 2021 studied human drivers' behavior on motorways in three different scenarios in a driving simulator. In the first scenario, the human drivers interacted with platoons of 2–3 connected and automated vehicles that were mixed in traffic consisting as well of manually driven vehicles (called 'Mixed' scenario). In the second scenario, the platoons of connected and automated vehicles drove only on a dedicated lane, which was chosen to be the left-most lane on a motorway consisting of 3 lanes (called Dedicated Lane scenario), while the third scenario consisted only of manually driven vehicles (called 'Base' scenario). It was found that human drivers accepted smaller gaps during lane changing maneuvers in the dedicated lane compared to the Mixed and Base scenarios, with up to 12.7% shorter gaps at on-ramps.

In terms of lane-changing behavior, an increase in lane-change duration was observed when HDVs interacted with platoons of AVs (Lee & Oh, 2017; Lee et al., 2018). It was found that the participants experienced a higher psychological burden while driving near platoons of automated vehicles, leading to an increase in lane change duration (Lee & Oh, 2017).

The above studies point to the behavioral adaptation of human drivers when they interact with AVs. However, these studies assume that AVs drive differently than HDVs. Also, most of these studies focused on AV platoons, while only a few on one-to-one HDV-AV

Table 1
Studies focusing on understanding the interactions between HDVs and AVs.

Study	Driving behavior	Sample size	Country	Main Findings for Human drivers
Controlled field tests				
Mahdina et al. (2021)	Car-following	9	United States	HDV drivers exhibit lower driving volatility in terms of speed and acceleration. HDV drivers maintain slightly smaller headways with AVs.
Zhao et al. (2020)	Car-following	10	China	AV believers – Small headways maintained with AVs. AV skeptics – Large headways maintained with AVs. AV neutral – No difference in driving behavior between AVs and HDVs
Rahmati et al. (2019)	Car-following	9	United States	Small headways and smoother driving while following AV in comparison to HDV
Driving simulator studies				
Rad, Farah, Taale, van Arem, & Hoogendoorn, 2021	Car-following and gap acceptance	51	The Netherlands	HDV drivers kept smaller headways during car-following and accepted shorter gaps during lane changing in a dedicated lane scenario compared to mixed and base (0% AVs) scenarios.
Schoenmakers et al. (2021)	Car-following	34	The Netherlands	Shorter time headways near AV platoon when driving in the proximity of a continuous-access or limited-access dedicated lane compared to limited-access dedicated lane with a guardrail
Trende et al., 2019	Gap acceptance	17	Germany	Under time pressure drivers have a higher probability to accept a gap at an intersection when interacting with AVs compared to when interacting with HDVs
Lee, Oh, and Hong (2018)	Lane change	30	Republic of Korea	Increase in lane change duration with an increase in AV penetration rate
Lee and Oh (2017)	Lane change	30	Republic of Korea	Increase in lane change duration near AV platoon due to psychological burden
Gouy (2013); (Gouy et al., 2014)	Car-following	42	United Kingdom	Decrease in time headways near AV platoon

interaction. Therefore, there is a need to study potential behavioral adaptations when AV behaves similarly to HDV and when drivers are provided with information regarding the AV.

Trust in AVs plays a major role in shaping the expectations of human drivers towards the driving behavior of AVs. However, trust is highly influenced by the knowledge and information about AVs. Feldhütter, Gold, Hüger, and Bengler (2016) showed that trust in AVs was affected by media and personal experience. From their study, a significant change in trust was found when the participants received basic information about AVs, read media articles, and when they have personally experienced AVs in a driving simulator. Ward, Raue, Lee, D'Ambrosio, and Coughlin (2017) found that trust and acceptability of AV technology varied greatly with the age of people and their knowledge about AVs. When participants were provided with positive knowledge and insights about AV technology, their perceived benefits of AV technology increased, and their perceived risks decreased, leading to an overall improvement in their trust in AV technology. A similar relation between trust and knowledge was also found by Nuñez Velasco et al. (2019).

Hagenzieker et al. (2020) studied the impact of positive and neutral information on cyclists' trust and perception towards inter- action with AVs. It was found that positive information regarding AVs increased the trust of cyclists regarding interacting with AVs. In another study by Vlakveld, van der Kint, and Hagenzieker (2020), the bicyclists yielded to the AV more often when they were provided with negative information regarding AVs. This suggests that providing information about AVs affects the interacting actor's perception of AVs.

Several studies found an influence of recognisability of AVs on the behavioral adaptation of road users. Many of these focused, however, on the interactions between AVs and Vulnerable Road Users (VRUs) with no consensus regarding the impact of recognis- ability (Dey, Martens, Eggen, & Terken, 2019; Hagenzieker et al., 2020; Velasco et al., 2019). In a simulation study by Fuest et al. (2020), no subjective or objective differences in driving behavior were observed, when AV was made explicitly recognizable. Given the lack of research, the effect of recognisability still needs to be investigated further.

Most of these studies used driving simulators, while only a few studies have collected empirical data from real-world driving (Rahmati et al., 2019; Zhao et al., 2020). Thus, more empirical research needs to be conducted to fill the research gaps regarding understanding the interactions between HDVs and AVs and in different maneuvers, such as car-following, lane-changing, and gap- acceptance. Therefore, this research investigates the potential behavioral adaptation of human drivers when interacting with recog- nizable AVs, with the help of a controlled field test.

The rest of the paper is structured as follows. Section 2 presents the research main objective and the underlying research question. Section 3 discusses the research methodology, experimental design, and data collection process. Insights into the data processing and analysis method are provided in Section 4. Section 5 presents the results of behavioral adaptation observed in different types of driving behaviors. Finally, section 6 concludes this paper with a discussion and recommendations.

2. Research objective and research question

The main objective of this study is to investigate one-on-one interactions between AVs and HDVs during early phases of automation when the penetration level of AVs in road traffic is not high enough to harvest the benefits of platooning. Therefore, the resulting research question is: What are the potential behavioral adaptations of human drivers during their interactions with an automated vehicle?

This research focuses on three driving behaviors:

- Gap acceptance at un-signalized intersections (critical gaps)
- Car-following behavior (longitudinal control)
- Overtaking behavior (longitudinal and lateral control)

In addition, this research studies the effect of positive/negative information about AVs on the driving behavior of human drivers and the change in their trust in the AV over multiple interactions.

3. Methods

A controlled field test was conducted in which human drivers interacted with both HDVs and AVs. The human drivers are referred to in this study as 'Participants'. The participants were asked to drive in their own vehicle (because of COVID-19 restrictions). During the field test, the participants interacted with an instrumented test vehicle that could be set up to appear as an AV. The instrumented test vehicle, referred to in this study as the 'Test Vehicle' (TV), collected data on the driving behavior of the participant during their interactions. The field test was approved by the Human Research Ethics Committee (HREC) of the Delft University of Technology, the Netherlands.

3.1. Field test location

The field test was conducted on a 3 km long straight road section in Noordzeeweg near the town of Rozenburg in the Netherlands. The selected location provided two parking lots on both sides of the road section, which were used as start/end locations of the participant and the TV. Also, a tower was present in the middle of the road section, which was used as a reference point. The test route had one 3.5-m wide lane per direction separated by dashed lane markings (i.e., overtaking was allowed). The traffic intensity of the test location was very low (around 30 vehicles per hour), and the speed limit of the road section is 60 km/h.

3.2. Field test setup

The experiment was designed in such a way that the participant drove between points A and B in his/her own vehicle, and the TV was driven between points 1 and 2 (see Fig. 1). In a single run of the field test, the participant either drove from point A to point B or vice versa, whereas the TV was driven from point 1 to point 2 or vice versa, respectively. A single run, therefore, was defined as driving the road stretch in one direction. The TV always started from the parking lot near the start location of the participant. In each run of the field test, the participant interacted with the TV, and the interactions included: gap acceptance, car-following, and overtaking. The participants were instructed to reach their end location as described in Fig. 1.

At the start of each run, the participant and TV positioned themselves in their respective starting locations. The participants were instructed to start from point A and reach point B while the TV drove from point 1 to point 2. The interactions between the participant and the TV took place in the following manner:

1. **Gap acceptance:** A run began when the TV started driving from its start location point 1 and approached the participant (point A) at a constant speed of 40 km/h. This speed provided ample opportunity for the participant to observe the type of vehicle (as anecdotally confirmed by all participants). From the participant's perspective, the TV approached from its right-hand side in the opposite (further away) lane. When the TV was approaching the participant in the approach zone (blue zone in Fig. 2), the participant was expected to indicate the last moment when she/he would decide to merge in front of the approaching TV, i.e., their critical gap. The participant indicated the critical gap through a hand gesture (putting the hand down when it was not safe to cross anymore (Fig. 2, top)). However, the participant was not expected to take any action at this point for safety reasons.

2. **Car-following:** Once the TV had crossed the parking lot at point A and entered the car-following zone, the participant was instructed to start driving towards its end location (point B). When the participant started driving, the TV gradually accelerated from 40 km/h to 60 km/h (speed limit of test location). As the TV reached the speed limit of the road in this section, there was not enough incentive for the participant to overtake the TV. Thus, the participant followed the TV for approximately 1-kilometer distance (~1-minute driving) at a speed of 60 km/h.

3. **Overtaking:** At the end of the car-following zone (recognized by the tower landmark), the TV gradually slowed down to 40 km/h, triggering the participant to overtake (Fig. 2, bottom). The slowing down took place at one of the three randomly chosen slow-down points SP1, SP2, and SP3 (Fig. 1). SP1 and SP3 were located 200 m before and after the center of the landmark point (SP2). Within the overtaking zone, the participant had to decide whether and when to overtake the TV. Two types of overtaking maneuvers were identified: A flying overtaking maneuver in which the participant directly overtook the TV without the need to decelerate and adjust its speed, and an accelerative overtaking when the participant followed the TV before overtaking (Hegeman, 2004). The overtaking was possible within the next 800 m before reaching the end location of the participant. After an overtaking by the participant, the speed was restored to 60 km/h, and the TV was driven behind the participant.

After these sequential interactions, the participant stopped at its end location point B, and the TV proceeded straight to its end location point 2. In the next run of the experiment, the participant was driven from point B to point A. In this case, the approach zone was between point 2 and point B, followed by a car-following zone and an overtaking zone. The interaction at point B was similar to point A as the TV approached from the right of the participant and drove on the opposite (farther) lane.

3.3. Scenarios

To observe any differences in the driving behavior of the participants during their interactions with the AV, the interaction with the TV was carried out in two scenarios. In one scenario, the TV was driven as an HDV, whereas, in the other scenario, the TV was driven appearing as an AV. In practice, in both scenarios, the TV was driven manually by the same professional driver, but in AV scenarios, the driver held the lower part of the steering wheel, while in the HDV scenarios, he held the upper part of the steering wheel, making his hands clearly visible (Fig. 3, top vs. middle). The scenarios were named i-HDV and i-AV, where 'i' refers to interaction with the TV, either as an HDV or as an AV, respectively. The i-AV scenario was easily distinguishable from the i-HDV scenario by the fake LiDAR
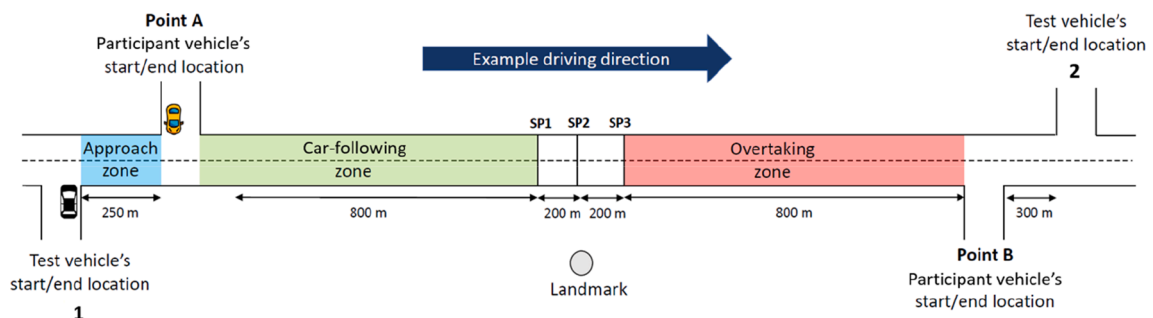

Fig. 1. The experiment field test plan (SP1, SP2 & SP3 indicate slow-down points).

Fig. 2. (Top) Participant performing a hand gesture to indicate the last moment when she/he would decide to merge in front of the approaching vehicle. (Bottom) Start of overtaking near slow-down point (tower) from TV's rear camera perspective.

placed on the vehicle roof and a sticker saying "Self-driving" on the side of the vehicle (Fig. 3, top vs middle). To ensure that the participants could differentiate the i-AV scenario from the i-HDV scenario, they were provided with a pre-experiment briefing, where they were shown a picture of the vehicle in i-HDV and i-AV scenarios, and an explanation on how they could notice the differences.

The experiment was designed carefully in such a way that the driving behavior of the TV in i-HDV and i-AV scenarios, was similar. The following precautions were taken to minimize differences in the driving behavior:

1. The TV was always driven by the same professional driver for all participants and in all scenarios.
2. The TV speed was kept as constant as possible in the different road sections within all scenarios, i.e., 40 km/h in the approach zone, 60 km/h in the car-following zone, and 40 km/h in the overtaking zone.
3. In case any disturbances in the speed occurred due to unavoidable circumstances, such as interaction with other road users, the data from such run were removed from the analysis.

Fig. 3. Test vehicle in i-HDV scenario (top) and i-AV scenario (middle and bottom).

Each participant interacted with the TV over 10 runs of which the first run was a trial run, 3 runs were i-HDV scenarios, and 6 runs were i-AV scenarios. The scenario during the first run was always i-HDV. For the rest of the 9 runs, the scenarios (i-HDV and i-AV) were randomized to counterbalance the order of encountered scenarios.

Before the last 3 runs of i-AV scenarios, positive or negative information regarding the AV behavior was provided to the participants in a written form (the information was provided only once). The type of information a participant would receive was randomly selected to achieve an equal number of positive and negative information recipients. The positive and negative information provided were as follows:

Positive information: "*The self-driving vehicle you are interacting with tends to avoid risks by driving very safely. It can fully detect its environment and it is able to accurately predict the behavior of other road users, which ensures safe driving.*"

Negative information: "*The self-driving vehicle you are interacting with cannot always fully detect its environment. This may cause to not correctly predict changes in its environment, leading sometimes to unsafe situations.*"

Fig. 4 summarises the number of runs for each type of scenario:

3.4. Vehicle and test location instrumentation

To collect data, a Toyota Prius (driven as TV) was instrumented with cameras, point Light Detection and Ranging (LiDAR), and a Global Positioning System (GPS) module as shown in Fig. 5. This vehicle was also instrumented with a detachable fake LiDAR and 'Self-driving' sticker to inform the participants whether it is driving in an AV or an HDV mode.

The point LiDARs were installed on the left, right, and rear of the TV to measure the distances of the nearby vehicles. The left and right LiDARs were installed near the rear door's handles, whereas the back LiDAR was installed on the rear bumper. The angle of the LiDARs was adjusted such that its beam stays parallel to the road surface, thus giving measurements only from reflection by objects.

To capture the video footage of the interacting participants and the surroundings, four cameras were installed on the left, right, front, and rear sides of the TV. The TV had an inbuilt GPS module that recorded the location and speed of the vehicle. A GPS module was also placed in the participant vehicle to record its location and speed.

For the data collection of critical gaps, field cameras were fixed on both parking lots A and B facing towards the parking lot to capture the hand gesture of the participant indicating the last moment of merging. Also, traffic cones were placed in the approach zone to estimate the approximate distance of the TV at the time of critical gap indication (see Fig. 6).

3.5. Participants

A total of 18 male participants were recruited for the field test. The participants were asked to sign an informed consent form before taking part in the experiment. Fourteen participants were between 35 and 60 years old, and 4 participants were younger than 35 years old. The participants were highly educated: 12 had a Ph.D. or MSc, 4 had a BSc, and 2 had secondary education. Fifteen participants were employed full-time, out of whom 12 participants belonged to science, technology, or engineering field. The participants were experienced drivers with a minimum experience of 7 years, and 15 participants had a driving experience of more than 10 years. Several participants had driving experience with various Advanced Driving Assistant Systems (ADAS): 9 had experience with Adaptive Cruise Control (ACC), 9 with Lane-Keeping Systems (LKS), 6 with Forward Collision Warning (FCW), and 4 with Automatic Emergency Braking (AEB). One participant had experience with SAE level 2 automation.
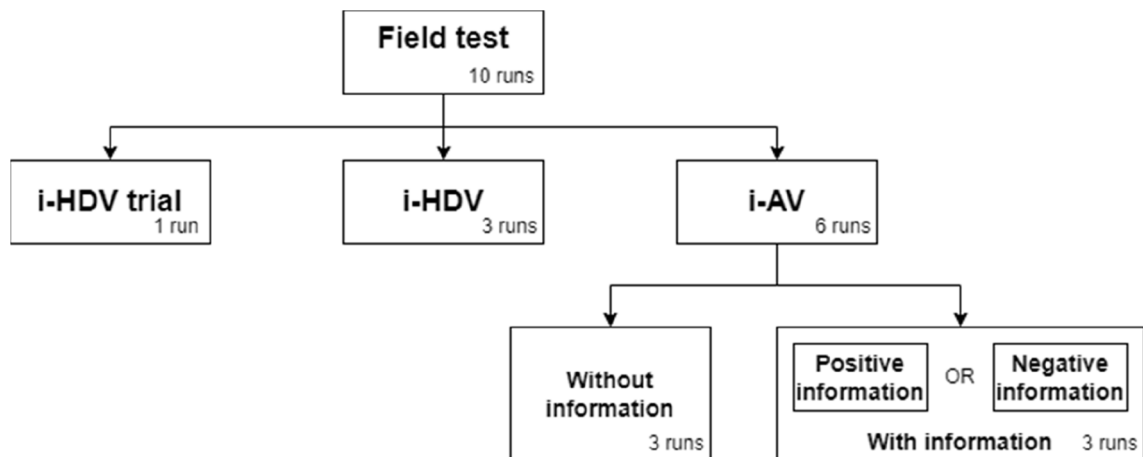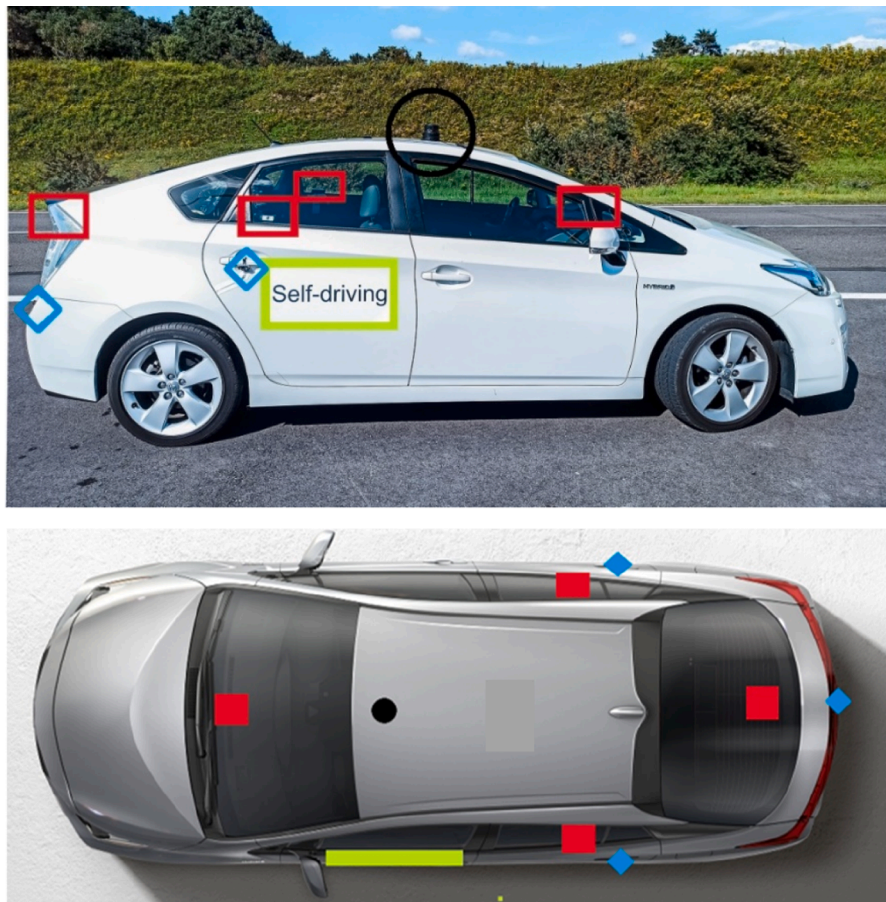

Fig. 4. Scenario design for the field test and the number of runs for each type of scenario.

Legend

Camera · LiDAR · Fake LiDAR · Self-driving sticker

Fig. 5. Test vehicle instrumentation.

3.6. Data collection procedure

Before the actual field test started, a pilot test was conducted on 14th July 2020, mostly to test the sensing equipment and the experimental procedure. After completing the pilot test, some small changes in the field test design were carried out. The final field test was carried out on 21st, 22nd, and 23rd July 2020. During these three days, the weather was clear and sunny. The traffic intensity of the test route was very low (around 30 vehicles per hour) during the field test days.

Before the field test, the participants were provided with pre-experiment questionnaires intended to collect their socio-demographics, general trust in AVs, and driving styles using the Multidimensional Driving Style Inventory (MDSI) developed by Taubman-Ben-Ari, Mikulincer, and Gillath (2004). The MDSI consists of 44 items that are ranked on a 6-point scale ("not at all" to "very much") and assesses four broad domains of driving styles: reckless and careless driving, anxious driving, angry and hostile driving, and patient and careful driving.

When the participants arrived, a briefing was provided to them, and their vehicle was equipped with a GPS module. The participants were provided with information regarding their destination and route and the speed limit of the road (i.e., 60 km/h). They were asked to drive as they would normally do in real life and were told that they could perform any necessary driving maneuvers. They were not explicitly told to overtake, but the speed reduction of the TV when approaching the overtaking section (as shown in Fig. 1) triggered the participants to overtake. At the recruitment phase, the participants were not informed that they would be interacting with AVs during the experiment; rather, that they would need to drive their vehicle from one point to another interacting with different vehicles. This was done to ensure that the participants do not build any expectations or perform any preliminary research regarding AVs before the actual field test. However, on the day of the experiment, the following measures were taken to ensure that the participants could differentiate the i-AV scenario from the i-HDV scenario:
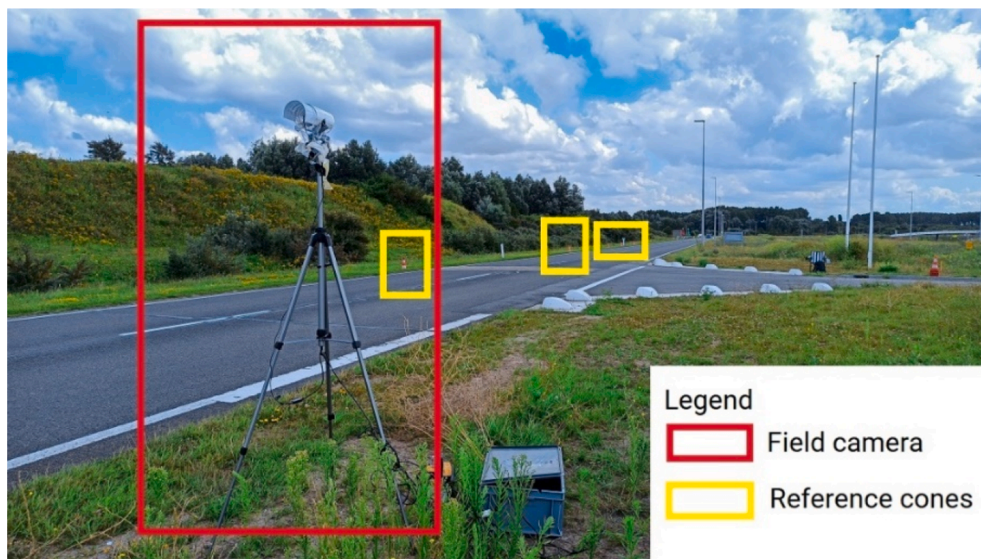
Fig. 6. Field camera and reference cone set up near the parking lot - point B.

1. The participants were briefed about how they could notice the difference between the AV and the HDV, and they were shown pictures of the two vehicles that illustrate these differences (as in Fig. 3).
2. When the experiment began, the participants started driving once they saw the TV crossing in front of them.
3. At the end of the first run with i-AV scenario, the participants were asked whether they were able to recognize the AV and differentiate it from the HDV.
4. At the end of the experiment, the participants were asked again in an interview if they had any difficulty recognizing the type of vehicle scenario. All the participants shared verbally that they were able to identify the type of vehicle by the fake LiDAR and sticker on the side of the vehicle.

After the briefing, the experiment started, following the field test setup previously discussed in Section 3.2. Other road users were also present during the experiment, which contributed to the realism in the experiment. However, the experiment was only started when other road users were not nearby. At the end of each run, the participant drove to its end location, where a team member assisted the participants in the realignment of their vehicle for the next run and reminded them to fill out the questionnaire regarding trust in the interacting TV and stress during the run. The TV drove to its end location out of sight of the participant, and it was prepared for the next run of the test by putting/removing the self-driving sticker and mounting the fake LiDAR. At the end of the experiment, the participant was provided with a post-experiment questionnaire and was interviewed for details about their observations and choices.

4. Data processing and analysis

The data processing included the processing of the sensor data and the questionnaire data.

4.1. Sensor data processing and analysis

The sensor data collected from multiple sources were synchronized using the timestamp indicated on the videos and the other

Table 2
Calculated driving behavior indicators and calculation methodology.

Driving behavior	Indicator	Unit	Calculation methodology
Gap acceptance	Critical gap	s	Based on GPS distance between the participant vehicle and TV at the moment the critical gap is indicated, and the speed of the TV
Car-following	Car-following headway	s	Median of time headway during car-following
Overtaking	Overtaking duration	s	Derived from the video
	Overtaking lateral gap	m	Based on distance measured by LiDAR
	Headway at start/end of overtaking	s	Based on the distance from camera observations and GPS speed
	Relative speed during overtaking	km/h	Based on GPS speed

devices. The sensor data was processed to collect various driving behavior indicators, as summarised in Table 2.

These indicators were calculated for each participant in each run. One observation of car-following behavior refers to the median of car-following headway for one participant for each run. To study the overtaking behavior, given its complexity, multiple indicators were defined and calculated, as illustrated in Fig. 7. These included the headway at the start of overtaking (A), the lateral gap during overtaking when the vehicles were in parallel positions (B), and the headway at the end of overtaking (C). The start of the overtaking was defined as when the front-left wheel of the participant vehicle crossed the centerline of the road, and the end of the overtaking was when the rear-left wheel crossed the centerline of the road.

As point LiDARs were used for data collection, due to the curved vehicle front body of the participant vehicle, the light cannot always reflect to the LiDAR, leading to inaccurate readings. Thus, GPS location was used for the time headway calculation. Headways larger than 6 s were considered to fall within a free-flow regime and were not considered as car-following (Vogel, 2002). Each GPS sensor had an accuracy of 4 m. Due to this high GPS error, headways at the start/end of overtaking were derived from videos manually. The lane markings of the road were used to approximate the distances.

During the data processing and calculations of the different indicators, disturbances and invalid observations such as participants failing to indicate the critical gap, disturbances by other road users, participants driving too far from the TV, and participants overtaking along with other road users were identified and removed from further analysis leading to a different number of observations per scenario and driving maneuver.

A detailed analysis of the processed dataset was carried out using descriptive statistics from which several insights regarding potential behavioral adaptation were gained. Furthermore, non-parametric statistical testing was performed to test the significance of the findings regarding drivers' behavioral adaptation.

4.2. MDSI questionnaire data processing and analysis

A score for each of the four driving styles for each participant was calculated based on the participants' answers, and the factor loadings provided by Taubman-Ben-Ari et al. (2004). Fig. 8 shows the box-whisker plot of self-reported scores of the four driving styles for all 18 participants.

Thus, to classify the participants based on their self-reported scores recorded for the MDSI questionnaire, a cluster analysis was carried out. The K-mean clustering resulted in 2 clusters of participants highlighting significant differences in terms of "Reckless and careless" and "Angry" driving styles. This indicated that the two clusters of participants differ in their aggression while driving, and thus, the participants were categorized into two groups: less aggressive (11 participants) and more aggressive (7 participants) drivers.

4.3. Drivers' characteristics as per information group

The participants were randomly assigned to the positive and negative information groups at the beginning of the field experiment. To check whether there is a significant difference in the characteristics of the drivers assigned to the two information groups, their age and driving styles were examined. No significant difference in age was found between the positive (mean age = 43.5, SD = 9.2) and negative (mean age = 41.2, SD = 10.0) information groups. Within the positive information recipients, there were 4 more aggressive drivers and 5 less aggressive drivers, while within the negative information recipients there were 2 more aggressive drivers and 6 less aggressive drivers. One participant who did not receive any positive or negative information due to technical difficulty during the experiment was also categorized as a more aggressive driver.

5. Results

Table 3 shows the number of valid observations per driving behavior per scenario after processing the collected data. The processed data were analyzed to gain insights into the three main driving behaviors: Gap acceptance, car-following, and overtaking.
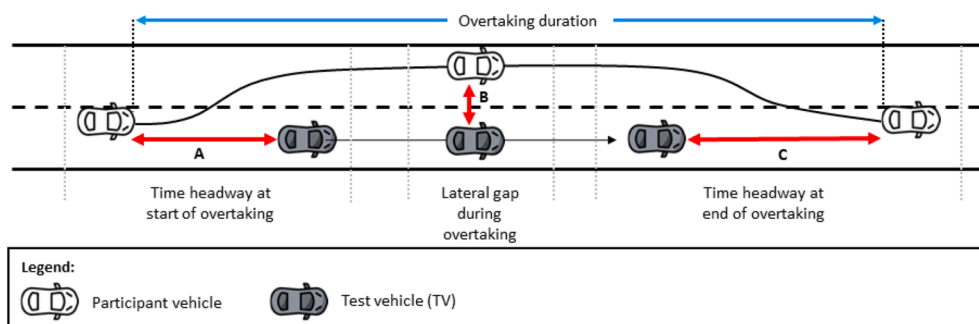

Fig. 7. An illustration of various indicators calculated to capture overtaking behavior.
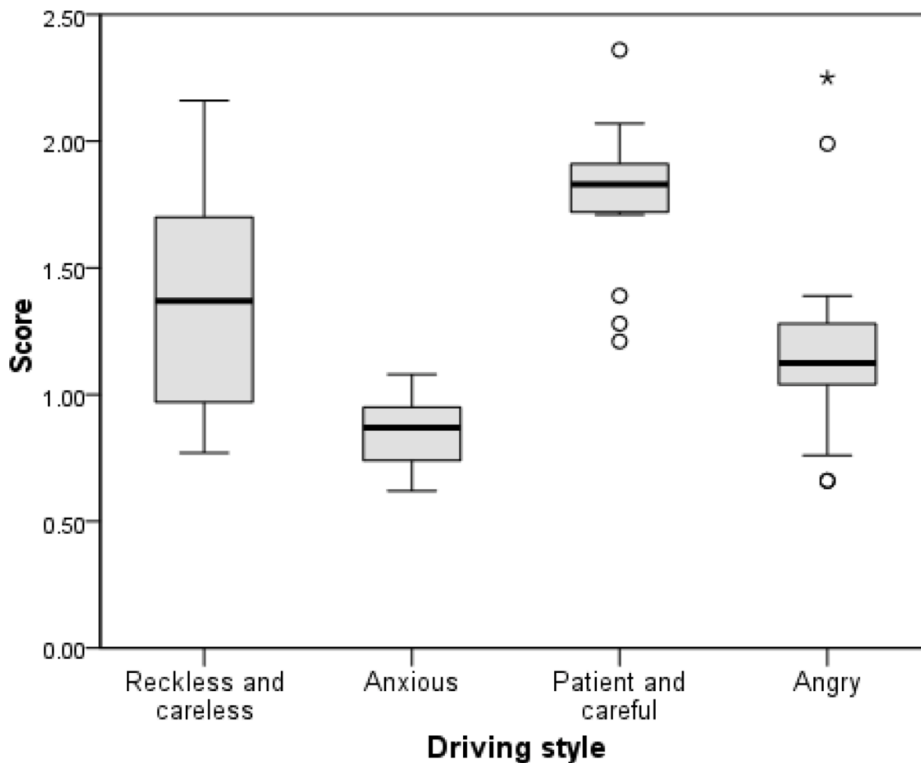
Fig. 8. Box-whisker plot of self-reported scores falling in different driving style categories (score range 0–5).

5.1. Gap acceptance behavior

Fig. 9 presents a boxplot of the indicated critical gaps of different participants in i-HDV and i-AV scenarios. It can be seen that the observed indicated critical gaps vary between the i-HDV and i-AV scenarios for the same individual. Due to differences in driving styles and personal characteristics, variation among the indicated critical gaps was also found between participants.

Fig. 10 (left) shows the boxplot of the indicated critical gaps in i-HDV and i-AV scenarios for all participants. The mean indicated critical gap in i-AV scenarios is significantly smaller than i-HDV scenarios (Wilcoxon Signed Ranks test, $Zvalue = -3.419, p-value = 0.001$).

Fig. 10 (right) shows the boxplot of the indicated critical gaps of participants receiving negative and positive information. The mean indicated critical gap was found significantly smaller in i-AV scenarios without information in comparison to i-HDV scenarios (Wilcoxon Signed Ranks test, $Zvalue = -5.232, p-value = 0.001$). The indicated critical gap values differ between the two groups because of individual differences between the participants that belonged to each group. The group receiving positive information was more balanced in terms of the number of more and less aggressive drivers, potentially leading to a wider spread of critical gap observations. However, the group receiving negative information was primarily dominated by the less aggressive participants, leading to less spread in critical gap observations. It was expected that the less aggressive drivers which mostly dominated the negative information group would have larger indicated critical gaps in comparison to the more aggressive drivers especially in the i-HDV and i-AV + No info

Table 3
Number of observations per scenario.

| Driving behavior	Indicator	Number of valid observations per scenario				
		i-HDV*	i-AV*			Total
			No info	Positive info	Negative info	
Gap acceptance	Critical gap [s]	69	51	24	23	167
Car-following	Car-following headway [s]	53	40	14	21	128
Overtaking	Overtaking duration [s]	53	39	18	22	132
	Overtaking lateral gap [m]	48	35	15	22	120
	Headway at start of overtaking [s]	51	38	19	22	130
	Headway at end of overtaking [s]	51	38	18	22	129
	Relative speed during overtaking [km/h]	52	38	19	22	131
* i refers to interaction with the test vehicle						
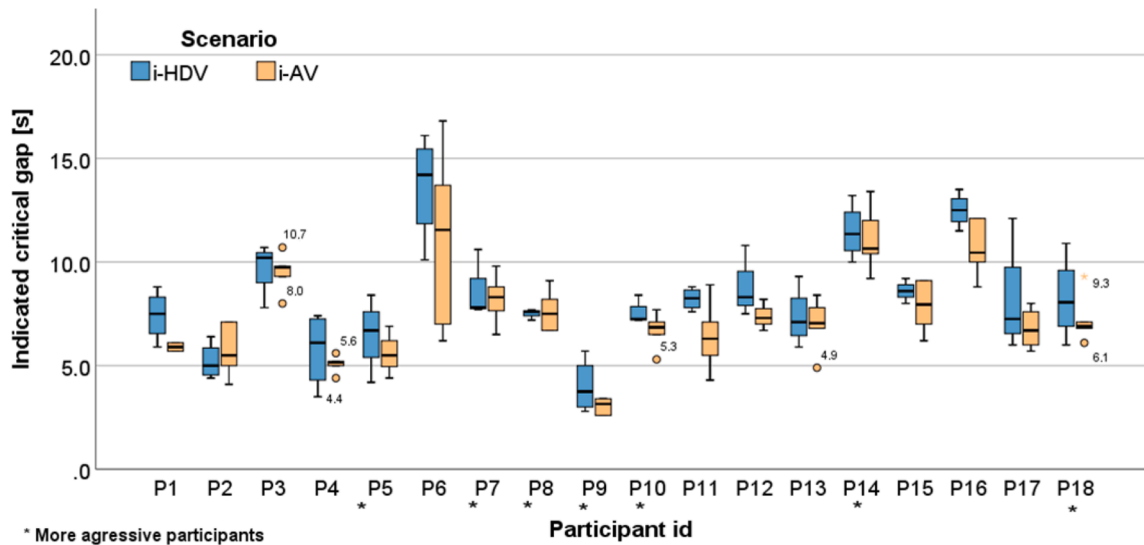
Fig. 9. Participants' indicated critical gaps in both scenarios i-HDV and i-AV.
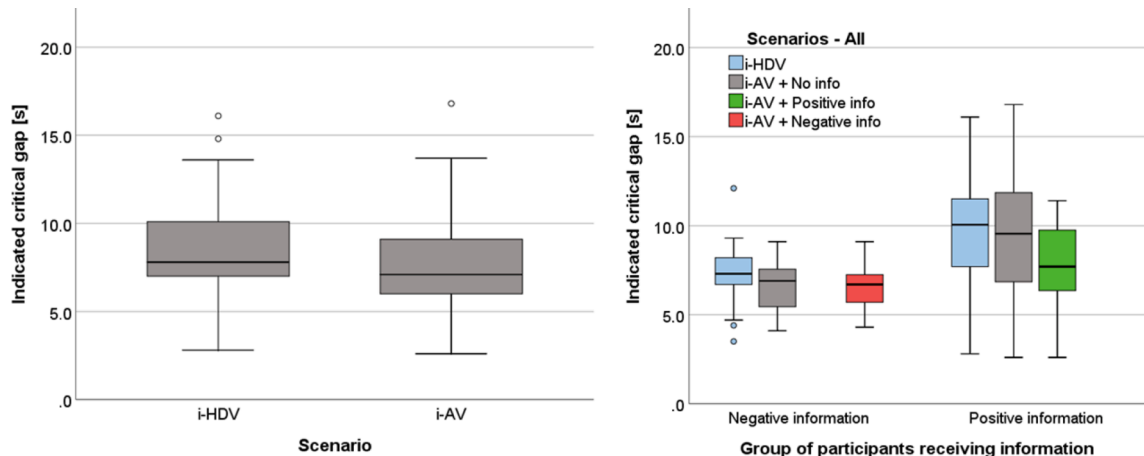

Fig. 10. Boxplot of average indicated critical gaps for 18 participants in i-HDV and i-AV scenarios (left) and within different information groups (right).

scenarios. However, the results in Fig. 10 (right) show the opposite trend. This counterintuitive observation could be due to the small number of participants in each of these groups.

To test the effect of information, Wilcoxon Signed Ranks test was performed to compare the indicated critical gaps in the i-AV scenario just before providing information and just after providing information. It was found that the indicated critical gaps decreased significantly just after providing positive information ($Zvalue = -2.033, p-value = 0.042$) (Fig. 10, right). However, no significant difference was found for the group that received negative information ($Zvalue = -1.014, p-value = 0.310$). Fig. 11 illustrates this again, but for each interaction. For i-AV scenario, when all interactions were averaged together for every participant, there was no significant difference in the mean indicated critical gap between positive and negative information groups, both, before providing information and after providing information (Mann-Whitney U test for both comparisons resulted in U(N (Pos) = 9, N (Neg) = 8) = 19.5 Z = -1.589 , p = 0.112). The means of the indicated critical gaps before providing information for the positive and negative information groups were 8.82 s and 6.72 s, respectively; and 7.59 s and 6.54 s after providing information for the positive and negative information groups, respectively. Despite that visually a significant difference appears to be between the two groups, a statistical difference was not found, which may be attributed to the small sample size in each of these groups.

The more aggressive driver group showed a reduction in the mean indicated critical gaps during their interactions with the AV. A significant negative correlation was found between the mean indicated critical gap and the mean reported trust in the AV over the multiple interactions ($r(39) = -0.343, p-value = 0.032$). However, in contrast, no significant correlation was found between their mean indicated critical gap and their mean reported trust when interacting with the HDV ($r(26) = -0.326, p-value = 0.104$). A similar correlation for the less aggressive drivers was observed during their multiple interactions with the AV ($r(58) = -0.372$,
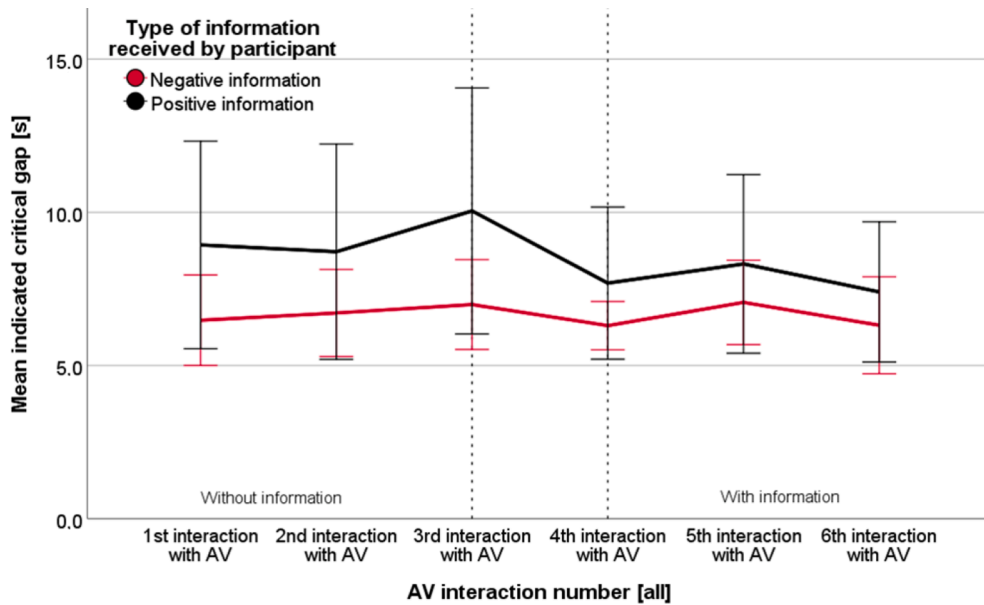
Fig. 11. Indicated critical gap per interaction with AV for different information groups (Error Bars: 95% CI; sample size = 17).

$p-value = 0.004$). However, this group also showed a significant negative correlation between the mean indicated critical gap and the mean reported trust when interacting with the HDV ($r(43) = -0.316$, $p-value = 0.039$).

5.2. Car-following behavior

To gain insights into the car-following behavior, median time headway during car-following was calculated for each participant and scenario. The speed profile of the TV was kept similar within all the scenarios. From the GPS analysis in the car-following zone, it was observed that the speed of the TV in the i-HDV scenario (mean = 52.3 km/h, median = 53.8 km/h, SD = 8.9 km/h) was very similar to the speed in the i-AV scenario (mean = 53.4 km/h, median = 54.8 km/h, SD = 6.7 km/h). Fig. 12 shows the scatter plot and boxplot of car-following headway observations for all participants in different scenarios. From the plots, it can be seen that half of the participants maintained higher headways with AVs than with HDVs, while the other half had the opposite trend. No statistically significant difference was found in car-following behavior between the two scenarios (Wilcoxon Signed Ranks test, $Zvalue = -0.355$, $p-value = 0.722$).

5.3. Overtaking behavior

Overtaking behavior was studied in terms of overtaking duration, overtaking lateral gap, relative speed during overtaking, headway at the start of overtaking, and headway at the end of overtaking. Mainly two different overtaking styles were observed during the experiment: flying and accelerative. Flying overtaking was witnessed more frequently than the accelerative overtaking style.
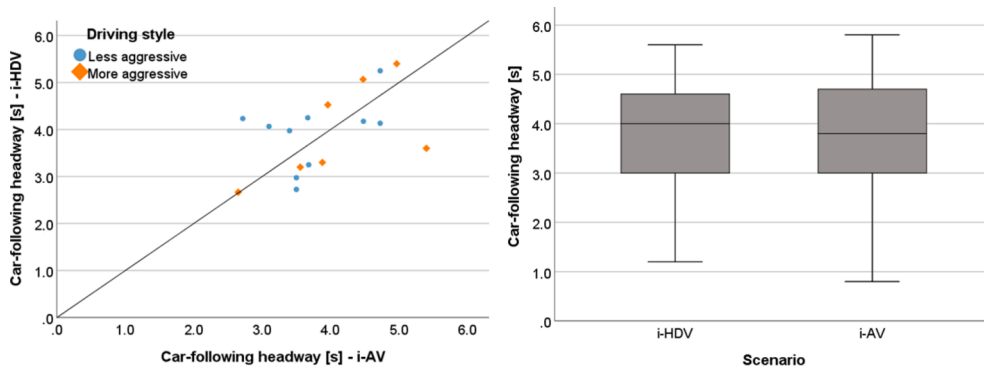

Fig. 12. Scatter plot (left) and boxplot (right) of median car-following headways in different scenarios (sample size is 17 as one participant had missing data).

A significant difference was observed in the overtaking behavior in terms of headways at the end of overtaking between AVs and HDVs. Fig. 13 presents the analysis of the mean time headway at the end of overtaking over the multiple interactions with the AV before and after receiving the information regarding the AV. It can be observed that the participants adopted significantly lower headways at the end of overtaking maneuvers of the AV (mean = 1.3 s) in the case of positive information scenario in comparison to the no-information scenarios (mean = 1.7 s) (Dunn's pairwise test, $Zvalue = 19.625, p - value = 0.007$), while for negative information, no significant difference was found (Dunn's pairwise test, $Zvalue = 8.375, p - value = 0.997$).

Also, headways at the end of overtaking maneuvers decreased over consecutive interactions with AVs (Fig. 14) within the accelerative overtaking style ($r(29) = -0.509, p - value = 0.005$), while for the flying overtaking style, no significant difference was found ($r(49) = -0.051, p - value = 0.728$).

5.4. Trust

To study the effect of trust within scenarios of different information, Wilcoxon Signed Ranks tests were performed. No significant difference was observed in the reported trust between AV and HDV scenarios ($Zvalue = -0.028, p - value = 0.977$). Within the group that received positive information, it was found that the reported trust was significantly higher in i-AV scenarios after providing positive information (Mean = 8.4, SD = 1.5) in comparison to the reported trust in i-AV scenarios before receiving this positive information (Mean = 7.9, SD = 2.2), ($Zvalue = -2.117, p - value = 0.034$). However, no significant difference in trust was seen i-AV scenarios for the participants receiving negative information (Mean = 8.2, SD = 2.1) in comparison to their reported trust in i-AV scenarios before receiving this negative information (Mean = 8.0, SD = 2.0), ($Zvalue = -0.137, p - value = 0.891$).

6. Discussion

In this study, the behavioral adaptation of human drivers when encountering AVs was observed in terms of gap acceptance and overtaking behavior but not in car-following behavior. For gap acceptance behavior, it was observed that the critical gap of drivers significantly decreased when they interacted with AVs compared to when they interacted with HDVs. This decrease in the critical gap was more prominent when positive information on the AV behavior was provided to the participants in comparison to no information. A similar impact was found for the headways at the end of overtaking maneuver, with the headway significantly decreasing when positive information regarding the interacting AV was provided. Therefore, positive information regarding the AV played a role in that drivers had smaller critical gaps and maintained significantly shorter headways at the end of overtaking. For the accelerative overtaking style, the headways at the end of overtaking decreased significantly with multiple interactions with the AV. For car-following behavior, there was no significant difference in the median headway when following an AV compared to when following an HDV. Furthermore, there were no significant differences between the HDV and i-AV scenarios in the overtaking duration, overtaking lateral gap, headway at the beginning of the overtaking, and the relative speed during overtaking.

The key finding of this research is that both interactions, gap-acceptance and merging back into the lane at the end of overtaking, are similar in the sense that the participants interacted with the AV in the "forward field of view" of the AV. These interactions differ from the other examined interactions (car-following, lateral gap, speed during overtaking, and headway at the beginning of overtaking) in that during the latter interactions, the participants have more control of the situation in terms of actively performing safe maneuvers and are responsible for maintaining safe distances from the test vehicle. However, in the former interactions, since the test vehicle drives behind the subject vehicle, the participants expect the test vehicle to take more control of the situation and maintain safe distances. The consistency of these findings further enhances the presence of behavioral adaptation.

The finding of no significant difference in the car-following behavior of drivers is opposite to findings from previous studies, which indicated that HDV drivers reduced their car-following headways while interacting with AVs or a platoon of AVs (Gouy, 2013; Gouy et al., 2014; Rahmati et al., 2019; Schoenmakers et al., 2021; Zhao et al., 2020). This could be due to the low accuracy of GPS sensors in this study and the relatively simple test environment. Also, the experiment was designed to maintain a constant speed of 60 km/h during car-following, which made it difficult to study car-following headways at different driving speeds. Therefore, further research is needed.

No significant difference was observed in the reported trust between AV and HDV scenarios. However, within the group that received positive information, it was found that the reported trust was significantly higher in i-AV scenarios after providing the positive information, while this was not the case for the negative information. This could indicate a possible interaction effect between trust and information. Positive information significantly decreased the participants' indicated critical gap when interacting with the AV, and trust was found to have a significant negative correlation with the participants' indicated critical gaps. As AVs are expected to be designed to interact safely and to drive defensively, these findings indicate potential exploitation of the technological advantages of AVs by the road users for their advantage.

Half of the participants in this study were also provided with negative information regarding the interacting AV. However, no significant effect of negative information was observed in their driving behavior and trust. One possible reason for this is the presence of a driver inside the test vehicle. The participants said that they were confident regarding the safety as a driver was always present for takeover in case something goes wrong. Another factor indicated by the participants is the simplicity of the test environment - the road having low traffic volumes, clear lane markings, and clear weather - in which it is less likely for the AV to fail in detecting its surrounding.

The findings of this research are in line with some findings in the literature. A driving simulator study by Trende et al. (2019) found that human drivers had a significantly higher gap acceptance probability at an intersection when interacting with AVs than HDVs and
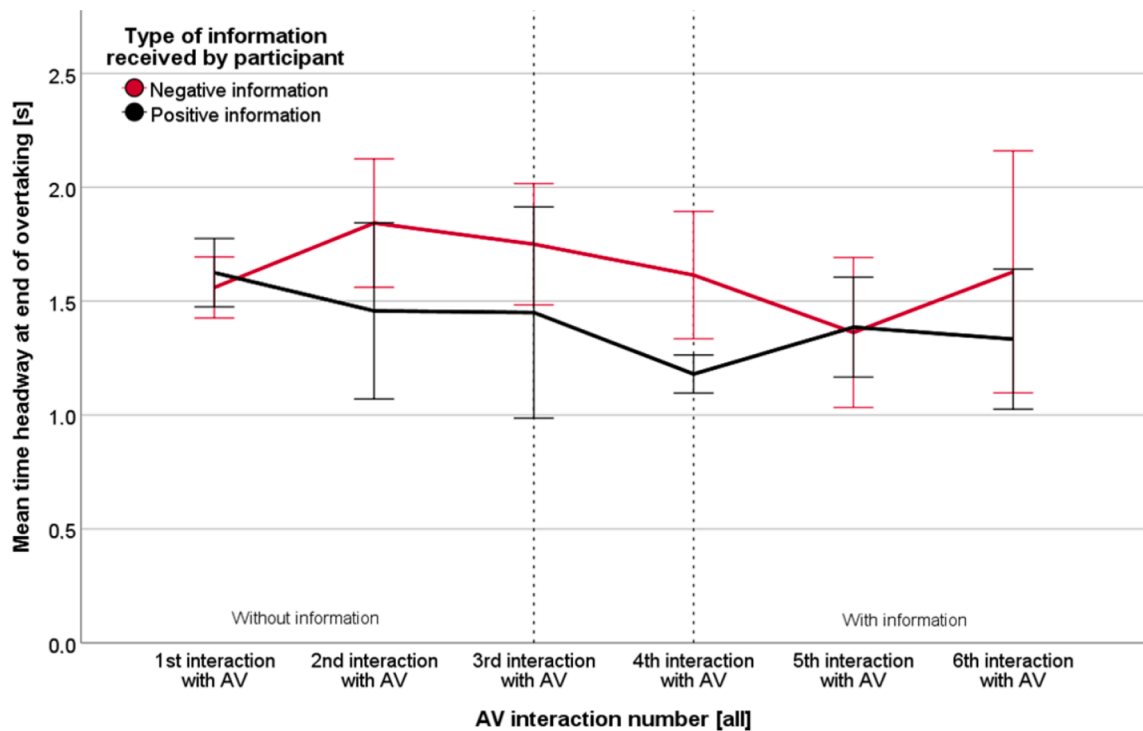
Fig. 13. Headway at the end of overtaking over multiple interactions with AV (within information groups) (Error Bars: 95% CI; Sample size = 17).
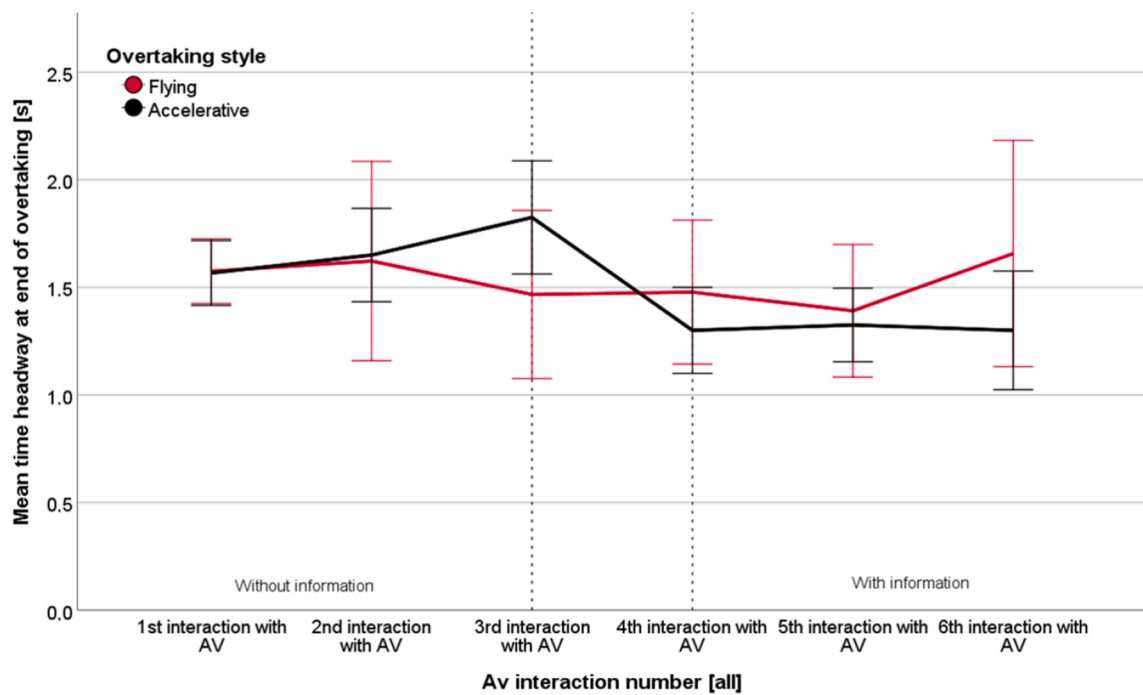

Fig. 14. Headway at the end of overtaking maneuver over multiple interactions with AV (Within different overtaking styles); Error Bars: 95% CI; Sample size = 17.

suggested that AVs can be technologically exploited by human drivers for their advantage, which is in line with our findings. The studies relating to lane change behavior indicated an increase in lane change duration while driving near a platoon of AVs (Lee & Oh, 2017; Lee et al., 2018). However, we did not observe any difference in terms of overtaking duration while interacting with the AV. This could be because we studied the interactions with one AV and not a platoon of AVs. Thus, an increase in overtaking duration may be attributed to higher penetration rates of AVs where platooning is possible. The only significant difference was observed in terms of headways at the end of overtaking, which indicated closer interactions with AVs.

AVs are perceived to have a greater ability to respond and are expected to take more control in performing safe driving interactions. This is also corroborated by the findings in Trende et al. (2019). With positive information, the trust in AV further increased and drivers had closer interactions with the AV. From a behavioral adaptation perspective, it can be concluded that closer (and more opportunistic) interactions with AVs can be expected in comparison to HDVs. More specifically, smaller gaps in front of the AV will be accepted. Thus, there is a potential for exploitation of AVs' technology by human drivers, and more abrupt merging (cut-offs) in front of AVs. For interactions from the rear and sides of the AV, no significant difference in driving behavior is expected based on the results of this study.

One immediate implementation of the results from this research is to investigate the effect of this behavioral adaptation on traffic flow and safety by using the empirical findings to adapt the parameters of the behavioral models in microscopic traffic simulation.

Various other factors such as age, driving experience, education, reported stress in different maneuvers, and weather were also taken into account for the analysis of behavioral adaptation. However, most of the participants had relatively similar personal characteristics. In addition, the weather was sunny on the days of the experiment. The participants were also asked about their stress levels (on a scale of 1 to 10) while performing different maneuvers. However, most of them did not report any differences in the stress between different scenarios. Therefore, the variation within these factors was not sufficient to observe any statistically significant differences in driving behavior.

7. Research limitations and future work

In this research, there are a few limitations. First, to ensure that human drivers could clearly recognize the AV during the interaction based on its physical features (fake LiDAR and sticker on the side of the vehicle), a pre-experiment briefing was provided to the participants. However, the recognisability of AV without providing any information is still questionable and needs to be investigated in future studies. Second, the sample of participants is not representative of the population as all the participants were male and experienced drivers. Also, the participants were mostly from the background of science and technology and therefore were capable of better understanding the technology of AVs. Therefore, it is recommended to investigate the behavior of groups of participants with a non-technological background.

Another area of future research is to study the effects of other influencing factors such as human drivers' characteristics, subject vehicle characteristics, and external factors on the change in driving behavior. Statistical models can be designed to identify the effect of individual or groups of factors contributing to behavioral adaptations. These models can then be implemented in microscopic traffic simulations to investigate the effect of such behavioral adaptations on traffic flow and safety. Furthermore, more data need to be collected to take into account different driving behaviors of AVs, different recognisability of AVs, absence of a driver in AVs, different road types and speed limits, the presence of other road users, and different environmental conditions such as weather, time of day, visibility, to cover the entire spectrum of behavioral adaptation with AVs. These factors may have a major influence on the decisions of human drivers. Additionally, behavioral adaptation is more associated with long-term interactions, therefore it is important to study various effects over longer periods. Thus, more field tests (and in more naturalistic settings) need to be conducted.

CRediT authorship contribution statement

Shubham Soni: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Project administration. **Nagarjun Reddy:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Anastasia Tsapi:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Bart van Arem:** Writing – review & editing, Supervision. **Haneen Farah:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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