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Investigating driver responses to automated vehicles in a bottleneck scenario: The impact of lateral offset and eHMI

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ABSTRACT

This driving simulator study investigated drivers' responses to an approaching automated or manual vehicle in a bottleneck scenario. Participants were asked to decide whether to pass through the bottleneck, or yield for the approaching vehicle, across numerous trials. Prior to each trial, they were informed whether the approaching vehicle was an automated vehicle (AV) or a manually driven vehicle (MV). Although participants were told that the MV was controlled by the experimenter using a distributed simulator, both vehicles were actually controlled by the system, and behaved in the same way. The kinematics of the approaching vehicle, such as its yielding behaviour (with or without lateral offset), and the presence of external Human Machine Interfaces (eHMIs, AV only) were manipulated. 40 participants took part in this study. Results indicated that participants' subjective responses and behaviours did not differ between the AVs and MVs. The approaching vehicle's lateral offset was seen to be the most influential source of information for participants, followed by information from the eHMI. Participants were more likely to pass through the bottleneck first, and had a shorter decision time, when encountering yielding vehicles with "away offsets", which involved the vehicle moving away from the road centre line. This condition also led to higher perceived safety, comprehension, and trust ratings. Conversely, drivers were more likely to yield and had a shorter decision time when encountering non-yielding vehicles without any lateral offset. The lateral offset of non-yielding vehicles did not have an impact on drivers' perceived safety and trust. However, non-yielding with "towards offsets" (towards the centre line) led to a higher comprehension score. Participants also passed through the bottleneck significantly more often and provided higher ratings for perceived safety and trust when the yielding vehicles presented an eHMI. This was regardless of lateral deviation. However, the eHMI only led to a higher rating of comprehension when the AV yielded without an offset. This study shows the value of using lateral offsets to communicate vehicles' intentions in bottleneck scenarios. While the eHMI could enhance the driver's understanding of the yielding AV, some participants also noted that it introduced uncertainty. Therefore, the need for eHMI should be further discussed.

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1. Introduction

Interaction occurs when at least two road users intend to occupy the same road space at the same time (Markkula et al., 2020). Conflicts between two or more road users often happen due to misinterpretation of others' driving intentions, behaviour, and communication (Ameen et al., 2021), which can be precursors to accidents. Conflicts could also lead to traffic congestion, impacting transportation efficiency and safety, particularly in driving scenarios with an unclear right-of-way (Gutiérrez-Moreno et al., 2022). To prevent conflicts in ambiguous road settings that have no formal traffic rules, vehicles must communicate their intentions and negotiate the right of way (Imbsweiler et al., 2018). One example is the bottleneck scenario, which requires human drivers to negotiate with each other as they attempt to pass through a single lane caused by cars parked on both sides of a two-lane urban road (Miller et al., 2022; Rettenmaier et al., 2019; Weinreuter et al., 2019).

In the foreseeable future, automated vehicles (AVs) will be integrated within our urban areas, interacting with other road users, such as manually driven vehicles (MVs), pedestrians, cyclists, and powered two-wheelers. Indeed, trials of these vehicles are currently taking place in North America and China (Hawkins, 2023; McKinsey, 2023). Hawkins (2023) underlined the necessity of effectively communicating an AV's status and intentions to prevent misunderstandings between road users. This is particularly vital for higher-level AVs such as those at SAE Level 4/5, which are not controlled by a human driver. Based on the communication between traditional vehicles and current AV technologies, Färber (2016) concluded that identifying a vehicle as an AV may lead to confusion and hesitancy among other road users, some may even exploit the AV's behaviour, given that AVs may not yet adhere to the established local and social driving customs. Studies found that human drivers drive more aggressively and are less willing to yield before AVs compared to manually driven vehicles, which could result in a more unsafe driving environment (Jiang et al., 2025; Lee et al., 2021; Liu, 2024; Liu et al., 2020; Youssef et al., 2024). Further research by Liu (2024) highlights related phenomena, including increased road rage and aggression from human drivers toward AVs, the exploitation of AVs' cautious behaviour, and negative peer influences of AVs on human driver behaviour. However, a Wizard of Oz study showed minimal variance in the time pedestrians took to make decisions when interacting with AVs compared to conventional vehicles at a crosswalk. Specifically, pedestrians were no more likely to hesitate before crossing in front of the Ghostdriver car than conventional cars, suggesting that they rely primarily on vehicle motion as a crossing cue (Moore et al., 2019). However, it is not yet known whether drivers have a different perception and behave differently when encountering AVs compared to MVs, and how they do so.

To date, an increasing number of studies have been conducted to investigate driver behaviours and communication strategies between AVs and MVs. Vehicle kinematic patterns including one-step and two-step deceleration behaviour, as well as driving to the edge of the road, have been used to demonstrate a vehicle's yielding behaviour during interactions at bottleneck scenarios. Conversely, maintaining speed and acceleration, and driving to the centre of the road tends to indicate a vehicle's non-yielding behaviour. Driving simulator studies have reported that lateral offset could increase traffic efficiency by reducing an MV's passing time through a bottleneck, as these were interpreted as more distinct compared to longitudinal movements. In addition, providing a lateral offset has the potential to increase traffic safety, and decrease the crash rate when the approaching vehicle insists on the right-of-way (Miller et al., 2022; Rettenmaier et al., 2021). However, the passing time through the bottleneck used in previous studies does not accurately measure drivers' decision-making times before reaching the bottleneck. No studies have explored the exact time point at which drivers make a yielding or passing decision before the bottleneck. In this study, a more precise metric will be used to determine when participants decide to pass or yield in bottleneck scenarios. This will allow for a more detailed exploration of the effects of longitudinal and lateral offsets on AV-MV communication in bottleneck scenarios.

External human–machine interfaces (eHMIs) can provide explicit information about an AV's intentions in ambiguous right-of-way scenarios. For example, Rettenmaier et al., 2019 reported that an eHMI deployed on an AV's bumper increased traffic efficiency in bottleneck scenarios. A video-based online study also reported that the extra information offered by HMIs on AVs improves MV drivers' subjective feelings and builds trust and acceptance of AVs in bottleneck scenarios (Li et al., 2023). Additionally, a field study by Papakostopoulos et al. (2021) demonstrated that eHMIs, such as externally presented lights, can provide information about an AV's yielding intentions. They found that the eHMI enhanced drivers' confidence in making crossing decisions at junction roads. Similarly, a driving simulator study (Avsar et al., 2021) reported that a novel light-band eHMI (Schieben et al., 2019) increased MV drivers' subjective perceived safety and acceptance of AVs in a T-junction. HMI signalling the AV's deceleration has been reported to increase the prosocial perception of the AV (Şahin İppoliti et al., 2023), while research has also found that displaying eHMI to human drivers earlier was rated as better for improving traffic efficiency compared to showing it later (Rettenmaier et al., 2020). These eHMIs were found to be particularly valuable for scenarios requiring road users to cooperate to negotiate the right-of-way. Rettenmaier & Bengler (2021) reported that combining eHMI and lateral offset was the most effective in reducing human drivers' passing times ahead of an AV in a bottleneck scenario. Furthermore, eHMI can be effective and safer in situations where a vehicle cannot move laterally towards the road's centre, and can be used to provide a salient message (Rettenmaier et al., 2020, 2021). However, to date, there has been little investigation of the impact of lateral offset and eHMIs on drivers' exact decision time before the bottleneck.

Drawing from these studies, this research aims to determine whether drivers' performance in response to an approaching vehicle in a bottleneck scenario is dictated by its movement patterns, or whether its identity (i.e., whether it is labelled as an AV or MV) influences driver behaviour. To examine the impact of different vehicular behaviours on drivers' performance, the approaching vehicles displayed two yielding behaviours and two non-yielding behaviours, combined with different types of lateral deviation, and the presence / absence of an eHMI. We posed the following research questions:

1. Does labelling an approaching vehicle as an AV or MV affect driver behaviour?
2. How does the AV's lateral offset influence human drivers' decision-making and driving performance?
3. How does the inclusion of an eHMI on the AV influence human drivers' decision-making and driving performance?

2. Method

2.1. Participants

After obtaining approval from the University of Leeds Ethics Board (Ref: LTTRAN-151), this experiment recruited a total of 40 participants (12 female, 28 male) with a mean age of 34.65 years (SD = 14.81; range = 21–79). Participants were required to hold a valid UK driver's license for at least one year. On average, participants had 12 years of driving experience (SD = 12.61; range = 21–79) and drove approximately 8506.25 miles per year (SD = 7473.01). The study recruitment was conducted through university mailing lists of participants who had signed up to take part in simulator studies. Participants received £15 compensation for their participation in this experiment.

2.2. Apparatus

This study utilized a fixed-based driving simulator located at the University of Leeds, as illustrated in Fig. 1. The setup displayed offered a controlled and secure setting for examining driving behaviours. Each simulator featured a 49-inch 32:9 monitor with a resolution of 3840 x 1080 pixels, a movable seat, and a steering wheel equipped with buttons for initiating trials. The accelerator and brake pedals were positioned on a stable Next Level Racing® Wheel Stand DD. The Simulator3 proprietary software, developed in-house, was used to program the scenario and vehicle behaviours, including engine sounds. A black opaque curtain separated the participant from the experimenter, who refrained from communicating during the study. Participants were informed that their simulator was synchronized with the experimenter's, allowing them to drive within the same virtual environment. The experimenter monitored participants via a webcam. During the MV trials, the experimenter simulated driving by operating the gas and brake pedals, creating authentic sounds to deceive participants into believing they were controlling the approaching vehicles. Further details are provided below.

2.3. Experimental design and scenarios

For this study, a bottleneck scenario was chosen as the interaction scenario. A within-subjects design was employed, whereby all participants underwent 32 trials (randomly presented by using the "RAND" function in Microsoft Excel). These trials involved three independent variables: the type of approaching vehicle, which included automated vehicles (AV) and manually driven vehicles (MV); the approaching vehicle's kinematic behaviour, which encompassed yielding without offset, yielding with an "away offset" (vehicle moves away from the road centre line), non-yielding without offset, and non-yielding with a "towards offset" (vehicle moves towards the road centre line); and, for AVs only, the eHMI status, which was either present or absent. Each trial incorporated different combinations of these variables to assess their impact on the participants' responses in the bottleneck scenario. Detailed information on these variables can be found in Table 1.

2.3.1. Type of approaching vehicle

At the beginning of each trial, a message appeared in the driving scene to notify participants whether they would encounter an automated or manually driven vehicle (see Fig. 2). However, as previously mentioned, the vehicle's behaviour was controlled by the software for all trials.

2.3.2. Vehicle kinematics

As shown in Fig. 3 and Fig. 4, the participant's vehicle (PV) was positioned in the centre of the lane at the beginning of the trial, while the approaching vehicle was situated 1.25 m from the edge of the road to ensure easy detection by the participants. At the start of

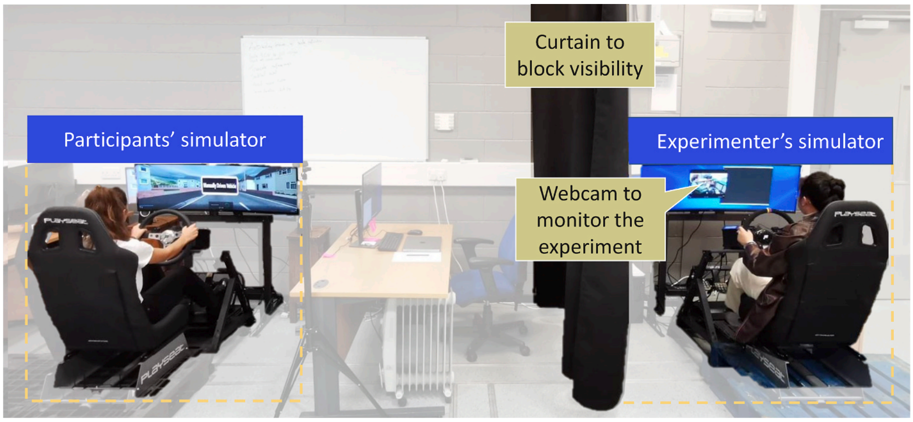


Fig. 1. Coupled driving simulators, showing the participant and experimenter, blocked by a curtain.

Table 1
Experimental Design – Number of trials in each condition.

Approaching vehicle's type	Approaching vehicle's kinematics	Presence of eHMI	No. of trials
Automated Vehicle (AV)	Yielding without offset	eHMI	2
	Yielding with "away offset"	eHMI	2
	Yielding without offset	No eHMI	2
	Yielding with "away offset"	No eHMI	2
	Non-yielding without offset	n/a	4
	Non-yielding with "towards offset"	n/a	4
Manually Driven Vehicle (MV)	Yielding without offset	No eHMI	4
	Yielding with "away offset"	No eHMI	4
	Non-yielding without offset	n/a	4
	Non-yielding with "towards offset"	n/a	4

Fig. 2. The tags shown on the participant's monitor at the start of each trial, which stated whether the approaching vehicle was (a) an AV or (b) an MV.

the trial, both the PV and the approaching vehicles (AV/MV) were at an equal initial distance to the bottleneck, which was 50 m away, and were traveling at the same speed of approximately 15 miles per hour (6.71 m/s). To initiate a trial, the participant pressed a button on the steering wheel and started to drive. Once the participant had moved 5 m from their starting point (i.e. was located 45 m from the bottleneck), the approach vehicle's movement was initiated, with the timings designed to ensure an interaction occurred.

The approaching vehicle then displayed one of four kinematic behaviours, as outlined below:

i. Yielding without offset: The approaching vehicle maintained a constant rate of deceleration, which started when it was 30 m from the middle of the bottleneck, coming to a stop when it reached a distance of 10 m from the bottleneck, see Fig. 3.
ii. Yielding with "away offset": The approaching vehicle deviated away from its initial lateral position and towards the PV by 1 m, during its' linear deceleration (see Fig. 3). However, if the participant decided not to pass the bottleneck, the approaching vehicle drove through the bottleneck after 5 s.
iii. Non-yielding without offset: The approaching vehicle maintained its' speed and started to steer to the middle of the bottleneck when it was 30 m from the bottleneck, see Fig. 4.
iv. Non-yielding with "towards offset": The approaching vehicle maintained its' speed and started to deviate an additional 0.6 m to the right when it was 30 m from the bottleneck (see Fig. 4).

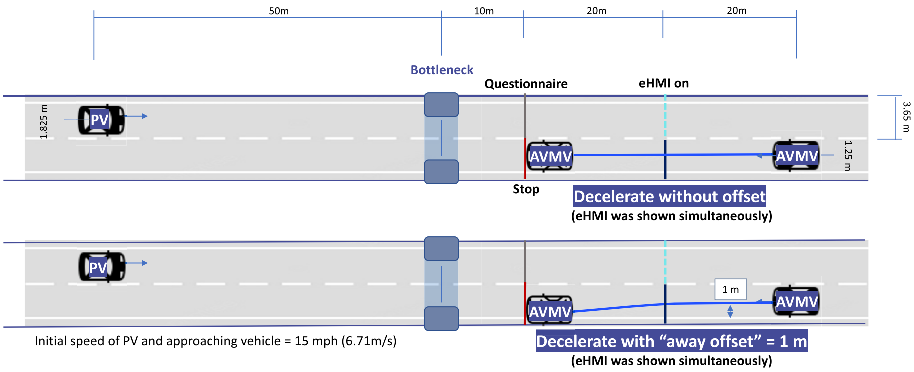


Fig. 3. Approaching vehicle's yielding behaviours.

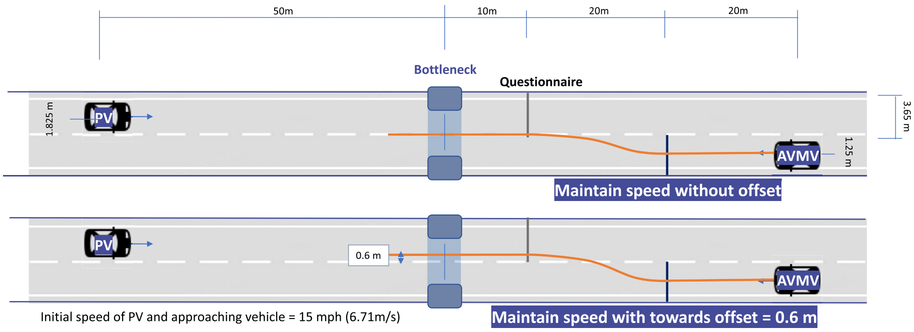
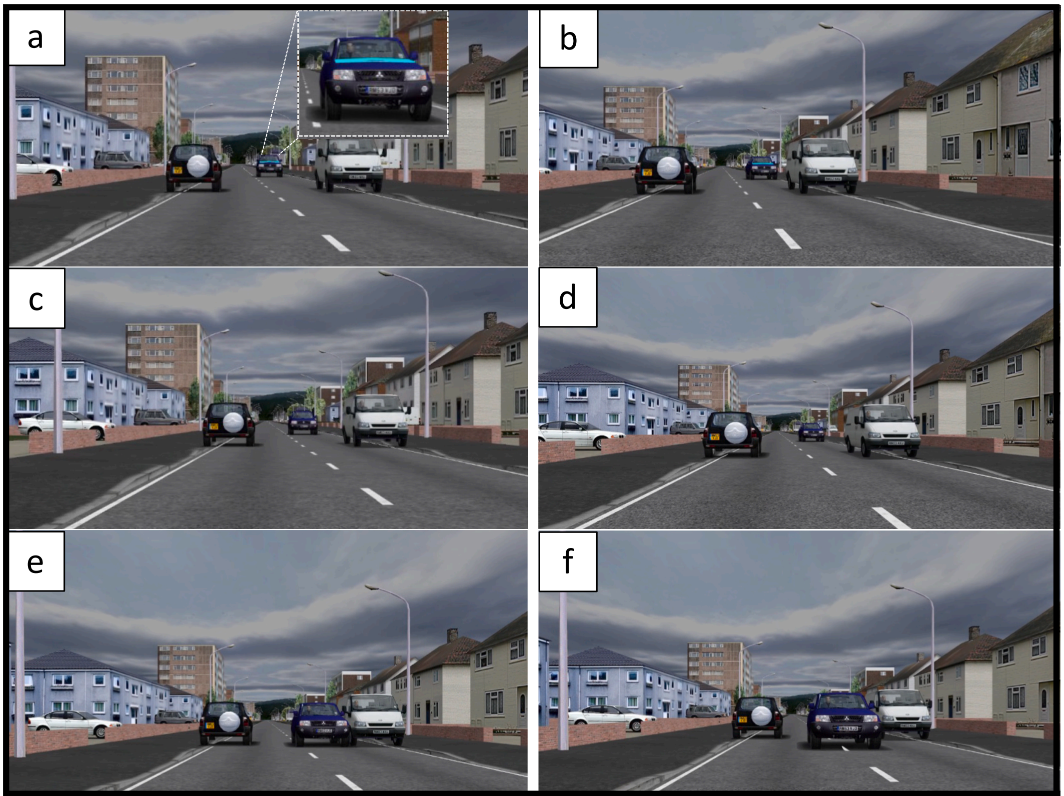


Fig. 4. Approaching vehicle's non-yielding behaviours.

2.3.3. External Human-Machine interface (eHMI)

In this study, participants were provided with information about the meaning of the eHMI in the Participant Information sheet. They were told that "*an external human–machine interface (eHMI) – a 360-degree cyan band is deployed on some of the automated vehicles, indicating the yielding intention of the approaching AV*". This 360° cyan light band has been successfully used to convey yielding intentions across a number of previous studies in the Horizon 2020 EU-Project 'interACT' (Kaup et al., 2019; Markowski, 2020; Schieben et al., 2019). The eHMI was presented in conjunction with the AV's deceleration onset, at 30 m before the middle of the bottleneck for both yielding conditions (see Fig. 5).



	Experimental condition		Experimental condition
a	Yield without offset, AV, eHMI	b	Yield with away offset, AV, eHMI
c	Yield without offset, AV/MV	d	Yield with away offset, AV/MV
e	Non-yield without offset, AV/MV	f	Non-yield with towards offset, AV/MV

Fig. 5. Examples of the experiment condition.

2.4. Procedure

Participants were provided with a participation information sheet via email approximately 48 h prior to the experiment. Upon arrival at the laboratory, the experimenter introduced the experiment to participants in detail again, "*You are required to drive through an urban city road which includes a section with parked cars on both sides, allowing only one car to pass at any one time (we call this driving scenario as bottleneck roads). The speed limit on this road is 20mph. On approaching the parked vehicles section with an initial speed of 15mph, you will encounter a vehicle from the opposite side. This vehicle may be controlled by the simulator software (automated vehicle, no human driver in charge with the driving tasks) or manually driven by the experimenter (manually-driven vehicle), At the beginning of each trial, a tag appears on the screen to indicate whether the approaching vehicle runs in autonomous mode or is controlled by the experimenter on the distributed simulator*". The participants then completed a demographic survey and engaged in a practice session to acquaint themselves with the simulator and experimental setup. For each experimental trial, participants were told that "*you are required to drive through the bottleneck road with parked cars on both sides, allowing only one car to pass at one time. You can decide whether to yield to the approaching vehicle – brake to allow the approaching vehicle to pass – or yield for the approaching vehicle*". If participants did not pass the bottleneck within 5 s after the approaching vehicle had yielded, the approaching vehicle would start to drive and pass through the bottleneck first. Each trial concluded automatically 10 m after drivers successfully passed through the middle of the bottleneck. Following each trial, participants completed a 5-point Likert scale in relation to the approaching vehicle (see Li et al. (2023)). After completing the final trial, participants took part in a brief interview (see Table 2), then, they were compensated and thanked for their participation. The entire study lasted approximately 60 min.

3. Results

A Generalized Linear Mixed Model (GLMM) was employed to analyze the data, taking into account the repeated measures experiment design, and the non-normally distributed data. GLMM is recommended for analyzing both binary responses and longitudinal data and is suitable for dealing with missing data (Rabe-Hesketh & Skrondal, 2010). The effect of lateral offsets, type of approaching vehicles, and the presence of eHMI on participants' decision-making and their decision-making initiation time was investigated. Given the differences in kinematic patterns of the yielding and non-yielding approaching vehicles, separate analyses were conducted to examine the effects of yielding and non-yielding trials on participants' driving performance.

For yielding trials, lateral offsets (without offset / with away offset) and vehicle types (AV with eHMI, AV without eHMI, and MV) were assessed using the percentage of passing decisions and the passing initiation time (PIT). PIT refers to the moment when participants decide to pass through the bottleneck first, specifically indicating the point in time when the participants initiated the last acceleration before reaching the bottleneck.

For non-yielding trials, the effect of lateral offsets (without offset / with towards offset) and vehicle types (AV / MV) on the percentage of yielding decisions and yielding initiation time (YIT) was evaluated. YIT refers to the moment when participants decide to come to a stop before the bottleneck. This metric was used to indicate the point in time when the participants initiated their final deceleration before reaching the bottleneck.

Following the data collection, the experimenter reviewed the recorded videos of each trial to identify any "incorrect decisions". For yielding trials, four specific situations were classified as "incorrect decisions". These were:

i. Did not pass: Participants stopped before the bottleneck, opting to wait for the yielding vehicle to pass first.
ii. Passed too late, resulting in collisions before the bottleneck: Participants had a delayed response, starting their movement when the approaching vehicle had already moved, leading to collisions.
iii. Did not pass and stopped too close to the bottleneck, resulting in a collision.
iv. Collisions after the bottleneck: Participants initially waited for the yielding approaching vehicle and stopped near the bottleneck. However, they subsequently decided to pass the bottleneck, resulting in collisions after passing through the bottleneck.

For non-yielding trials, two specific situations were classified as "incorrect decisions":

Table 2
Questions asked in the interview.

ID	Question	Question type
1	What information from the vehicle was important to help with your decision to pass/not pass? The given factors were "speed", "distance", "braking pattern", "offset (vehicle drives to edge or centre)", "knowing the approaching car is an AV or MV".	5-point Likert scale 1 "unimportant" 2 "slightly unimportant" 3 "neutral" 4 "slightly important" 5 "important"
2	Did knowing the approaching car is AV or MV affect your expectation and passing decisions? In what way? /Why not?	Open question
3	Did the eHMI (light-band) have an impact? In what way?/Why not?	Open question
4	During the experiment, was there any other information you would like to have had to decide it was safe to pass?	Open question

i. Stopped too close to the road centre and crashed.
ii. Passed through first and crashed.

The number of trials with "correct" decisions in each condition is shown in Table 3. When encountering yielding vehicles, there were 572 trials with passing decisions, 47 trials with non-passing decisions, and 21 trials with collisions. When encountering non-yielding approaching vehicles, there were 556 trials with yielding decisions and 84 trials with non-yielding decisions resulting in collisions.

The next section provides the results of the GLMM analysis.

3.1. Percentage of passing decisions when the approaching vehicle yielded

For the yielding trials, 619 trials in total were included in the analysis. 572 trials with passing decisions and 47 trials with non-passing decisions were compared, across vehicle type and lateral offset, using GLMM.

There was a significant main effect of lateral offset ($F\ (1, 61) = 23.44 p < 0.001$). Post hoc Bonferroni tests showed that yielding with an "away offset" led participants to pass significantly more often than trials without an offset. There was also a significant main effect of vehicle type ($F\ (2, 613) = 34.05$, $p < 0.001$), whereby the AVs with eHMI led participants to pass significantly more often than AVs without eHMI and MVs. There was no interaction effect ($F\ (2, 613) = 0.29$, $p = 0.79$), (see Fig. 6).

3.2. Percentage of yielding decisions when the approaching vehicles did not yield

For non-yielding trials, 640 trials were included in the analysis, which included 556 trials where the participant made a yielding decision and 84 trials with non-yielding decisions.

There was a significant main effect of the approaching vehicle's non-yielding lateral offset ($F\ (1, 636) = 17.74$, $p < 0.001$) on behaviour. Post hoc Bonferroni results showed that non-yielding without offset resulted in a significantly higher passing percentage than trials with a "towards offset". There was no significant main effect of vehicle type ($F\ (1, 636) = 6.47$, $p = 0.42$), and no interaction effect ($F\ (1, 636) = 0.23$, $p = 0.63$), see Fig. 7.

3.3. Passing initiation time (PIT)

572 trials were included in the pasting initiation time (PIT) analysis, the trials that "did not pass" and "with collisions" were excluded. There was a significant main effect of approaching vehicle's lateral offset ($F\ (1, 566) = 29.48$, $p < 0.001$), whereby yielding with an "away offset" (M = 5.15 s, SE = 0.19) led to significantly shorter PITs than without offset (M = 6.72 s, SE = 0.23). There was also a significant main effect of vehicle type ($F\ (2, 566) = 6.11$, $p = 0.002$), whereby encountering AVs with eHMI (M = 5.27 s, SE = 0.23) led to significantly shorter PITs than MVs (M = 6.33 s, SE = 0.21), but not compared to AVs without eHMI (M = 6.19 s, SE = 0.30). There was no interaction effect ($F\ (2, 566) = 0.92$, $p = 0.40$), see Fig. 8. Additionally, the approaching vehicle's lateral offset significantly affected participants' average speed during the trial ($F\ (1, 566) = 27.66$, $p < 0.001$). Participants had a faster speed when encountering vehicles yielding with an "away offset" (M = 4.84 s, SE = 1.73) compared to "without offset" (M = 3.94 s, SE = 2.20). Vehicle type also significantly affected participants' average speed ($F\ (2, 566) = 14.58$, $p < 0.001$), whereby encountering AVs with eHMI (M = 5.05 s, SE = 1.67) resulted in significantly higher speeds than AV without eHMI (M = 4.13 s, SE = 2.03) and MVs (M = 4.21 s, SE = 2.11).

3.4. Yielding initiation time (YIT)

556 trials were included in the yielding initiation time (YIT) analysis. There was a significant main effect of the non-yielding vehicle's lateral offset on YIT ($F\ (1, 552) = 133.91$, $p < 0.001$), whereby encountering a non-yielding vehicle with towards offset (M = 10.75 s, SE = 0.19) led to a significantly longer YIT than those without offset (M = 13.91 s, SE = 0.20). There was no significant main effect of vehicle type ($F\ (1, 552) = 0.41$, $p = 0.52$), and no interaction effect ($F\ (1, 552) = 0.04$, $p = 0.85$), see Fig. 9. Additionally, there was a significant main effect of approaching vehicle's lateral offset ($F\ (1, 552) = 131.21$, $p < 0.001$), Participants had a slower average speed encountering vehicles "with towards offset" (M = 3.23 s, SE = 0.66) compared to "without offset" (M = 3.84 s, SE = 0.71).

Table 3
The number of trials with correct decisions across approaching vehicle types, behaviours and eHMI.

	Yield without offset	Yield with away offset	Non-yield without offset	Non-yield with towards offset
	Number of passing		Number of yielding	
AV with eHMI	78 (97.5 %)	80 (100 %)	/	/
AV without eHMI	64 (80 %)	77 (96.3 %)	149 (93.1 %)	130 (81.3 %)
MV	123 (76.9 %)	150 (94.4 %)	147 (91.9 %)	130 (81.3 %)
Total	572 (89.3 %)		556 (86.9 %)	

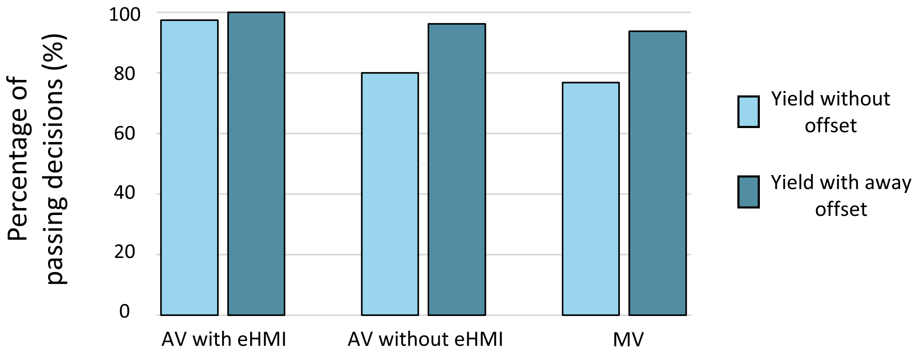


Fig. 6. Percentage of passing decisions when participants encountered yielding vehicles.

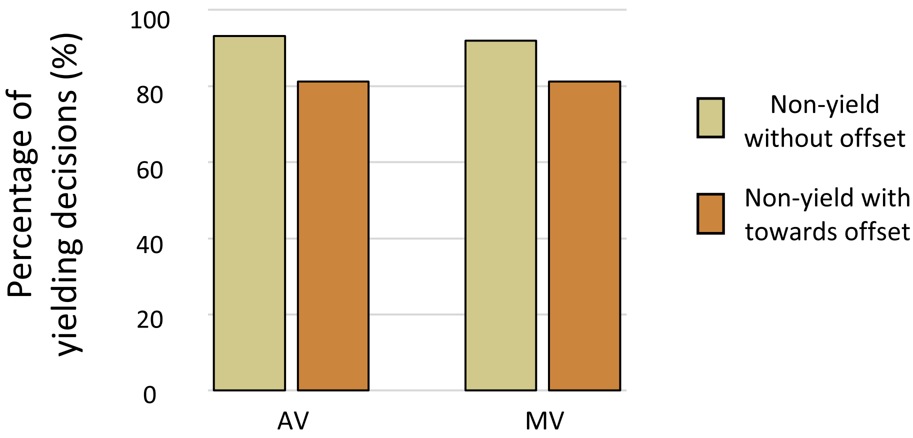


Fig. 7. Percentage of yielding decisions when the approaching vehicle did not yield.

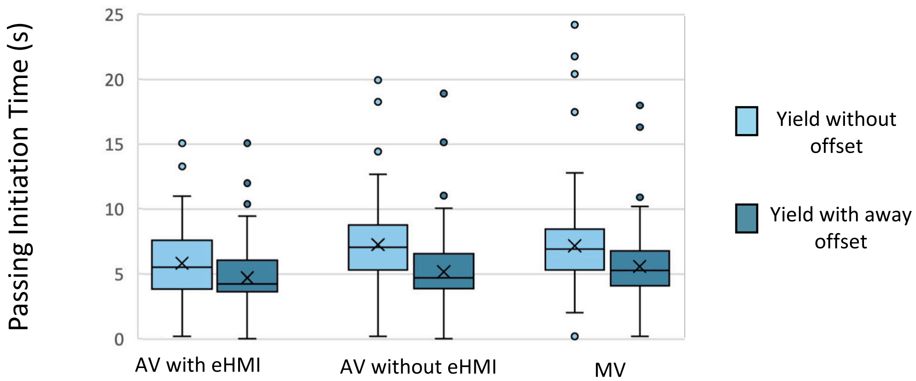


Fig. 8. Participants' passing initiation time (PIT) when encountering yielding vehicles.

3.5. *Interview analysis*

Interviews were automatically transcribed using the transcription function on Microsoft Teams, and these transcripts were then manually checked and revised by the authors.

3.5.1. *Factors affecting drivers' decision making*

The first question we asked participants was to rate the importance of the factors influencing their passing or yielding decisions using a 5-point Likert scale. Of the 40 participants, 35 considered "offset" to be an important factor affecting decision-making, followed by "braking pattern" (28 participants), "speed" (26 participants), "distance" (22 participants), and "AV or MV" (4 participants). None

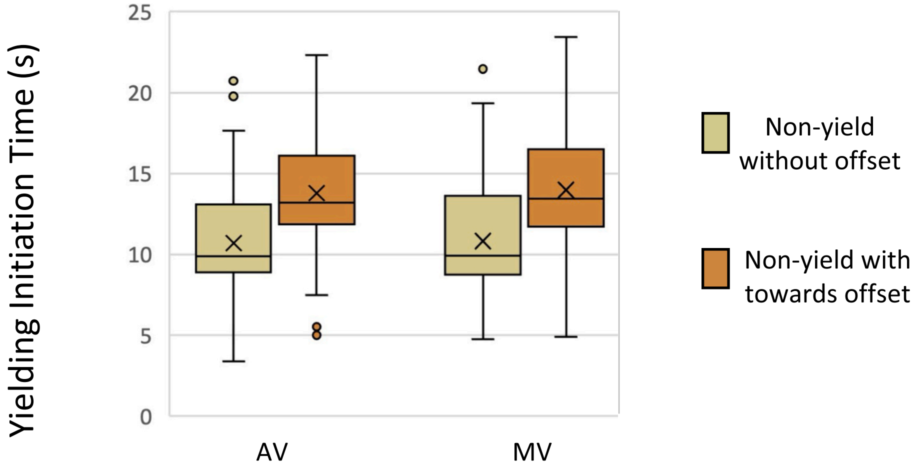


Fig. 9. Participants' yielding initiation time (YIT) when encountering non-yielding vehicles.

of the participants rated "offset" as unimportant, while 9 participants considered "AV or MV" to be an unimportant factor in their decision-making, see Fig. 10. Specifically, all 35 participants emphasised that the "away offset" was helpful in the decision-making of passing through the bottleneck, as indicated in interview comments such as "*driving to the edge is definitely important,*" "*the easiest form was to see if the vehicle drove over to the edge,*" "*I trusted more if they pulled up, and I can brake quickly and earlier.*", and "*moving to the edge of the road is important when I decided to pass*". Speed and distance also played a crucial role, with participants noting, "*of course I'm judging the speed as well*", "*how fast oncoming vehicles were approaching the two parking cars helps*". For the non-yielding approaching vehicles, the answers regarding offset are inconsistent, for instance, 1 participant indicated "towards offset" is ambiguous, stating "*if the approaching vehicle goes to the centre, I know I need to slow down. But when the vehicle drives towards to the centre, I do not know when to brake*". Similarly, "without offset" was also considered ambiguous, for example, 1 participant stated that "*coming through but staying slightly to the left* (non-yield without offset) *is ambiguous*". Brake pattern and speed also influenced the decision-making, with participants noting, "*I know I should yield when the oncoming vehicle maintains speed without slowing down*" *and* "*not showing any obvious deceleration*". It is important to note that participants relied on multiple cues rather than a single factor when determining whether an oncoming vehicle was non-yielding or not.

3.6. Drivers' attitude towards AVs, MVs, and eHMI

We then asked participants about their attitudes toward the types of vehicles encountered. Out of the 40 participants, 31 stated that the type of vehicle did not seem to be a major factor influencing their decisions of passing or yielding, 8 stated that it did, and 1 was unsure. Specifically, 31 stated, "*I just check the approaching vehicle's behaviour*", "*not really, I would imagine that they follow a similar pattern as the human driver*", and "*not initially, the behaviour seemed pretty similar from both, so it didn't really play much of a factor at all*". They emphasized that key factors influencing their decisions were more related to speed, distance, braking patterns, and the distribution of vehicles. Only a small number of participants (N = 8) expressed differing expectations regarding the type of approaching vehicle. Specifically, 3 participants indicated a higher expectation for AVs compared to MVs, stating, "*I expected AVs to yield more than human drivers*", and "*I feel an automated car would drive better than a manual person*". However, they also noted, "*It did not significantly impact my own decisions*". On the other hand, 5 participants expressed a higher expectation for MVs over AVs, citing reasons such as, "*I do not trust and am unsure about computers and automated driving systems*", "*I feel safe with the manual vehicle*", "*I trust manual vehicles more because human drivers have experience*", "*My initial thought would be that if it's automatic, I should wait*", "*MV can react to me more*". One participant mentioned having no clear stance on their attitude towards AVs or MVs.

Finally, we asked participants about their attitudes toward the eHMI. 2 participants indicated that the eHMI did not solely dictate their decision to pass through the bottleneck, as they still relied on judgment based on other factors. 1 participant remarked, "*The blue light provided extra information, but the decision is still up to the driver*", while another mentioned, "*The blue light-band helped me with decision-making but I still rely on other cues like car positions and speed*". 2 participants mentioned that the eHMI light band created some uncertainty. 1 participant mentioned frustration with AVs equipped with eHMI stopping and proceeding very slowly through the bottleneck, leading to uncertainty about their intentions. While another participant stated, "*Unless the AV indicated its intention clearly, I might consider messing with it to confuse its systems*", a statement that suggests some uncertainty about how to interact with AVs equipped with eHMI. The remaining participants (N = 34) stated that the eHMI helped them understand the intentions of the AV, helped improve their trust in the AV, and allowed them to proceed with more confidence when they saw the light indicating the AV would yield. Specifically, 6 participants mentioned that the eHMI aided their better understanding of the AV's intention to yield the right-of-way, thus improving their confidence in making passing decisions. One participant remarked, "*The blue light was very obvious, it's almost like knowing someone is waving at you*", while another likened it to "*similar to how human drivers use signals*". 7 participants stated that the eHMI helped provide information and increased their trust and feelings of safety. 1 participant mentioned, "*I would say I would feel*

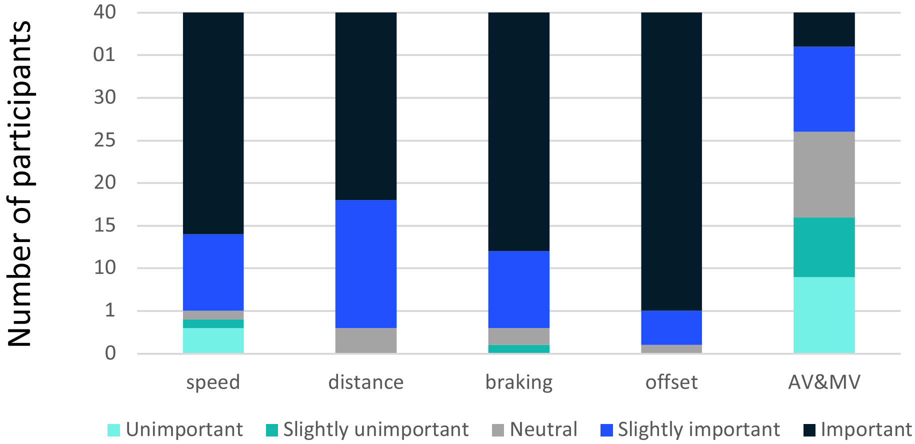


Fig. 10. Factors affecting participants' decision-making.

equally as safe around an automated car as a manual car when there was a blue light on the AV", while another expressed the feeling that "*I feel safer, more comfortable and confident when I decided to pass the bottleneck first*", and another stated "*when I saw the light, I knew that I should just go so I didn't slow down*".

4. Discussion

This study aimed to provide insights into the impact of various factors on drivers' decision-making and yielding behaviour during bottleneck scenarios. It investigated the effect of type of approaching vehicle (AV vs MV), its' kinematic features (i.e., its longitudinal and lateral offsets), and the presence or absence of an eHMI on drivers' subjective experiences and their driving behaviours (i.e., drivers' decision and initiation time).

Results showed that knowledge of whether a vehicle was automated or manually driven did not affect drives' subjective feelings (Li et al., 2023) or behaviours. Human drivers may have different expectations about automated and manual vehicles (Miller et al., 2022). However, the results showed that drivers' decision-making about whether to pass or yield to an approaching vehicle on a bottleneck road is based on the vehicle's kinematic behaviour, rather than whether it is labelled as a computer- or human-driven vehicle, especially if the two vehicles look exactly the same.

Our participants passed significantly more often, and with a shorter passing initiation time (PIT) when the approaching vehicles yielded with an "away offset", compared to the trials where yielding occurred without an offset. This observation is in line with previous research suggesting that integrating lateral movement cues radically improves the clarity of signals for yielding vehicles, particularly in ambiguous situations such as bottleneck scenarios (Miller et al., 2022; Rettenmaier & Bengler, 2021). When approaching vehicles did not yield, participants had a longer yielding initiation time (YIT) and passed less often when "towards offsets" were presented than when they were not. The "towards offset" also led to a higher number of collisions since it occupied the participants' lane excessively. Thus, we do not recommend this approach for the AV behaviour design, as it increases the risk of a collision.

Previous studies used passing / yielding duration to compare the impact of different conditions on drivers' decision-making times (Miller et al., 2022; Rettenmaier et al., 2021). Our methodology stands out in this approach by utilizing specific time points (PIT and YIT) to pinpoint the exact decision times. Compared to the duration, the time point is a more precise metric for knowing when the participants decide to pass and yield.

In terms of the value of eHMIs, the presence of an eHMI improved drivers' perceived safety and trust in a yielding AV (Li, et al., 2023). Participants passed through the bottleneck first significantly more often when encountering a yielding AV with eHMI compared to the trials without eHMI, regardless of whether this was accompanied by an "away offset". eHMI only led to a higher level of comprehension of AV behaviours under the "no offset" conditions, with no additional benefit when the approaching AV yielded with an "away offset" (Li et al., 2023). This illustrates that the participants prioritise interpreting vehicle kinematics over relying on eHMI. When drivers were able to accurately discern the intention of approaching vehicles through their movement characteristics, the influence of eHMI became negligible. These findings diverge from those of Rettenmaier & Bengler (2021), who observed an improvement in participants' comprehension of approaching AVs with an eHMI, both with and without an away offset. In addition, while the eHMI influenced participants' passing decisions, it did not significantly affect the passing initiation times (PITs), suggesting that its impact may be more pronounced at the decision-making stage rather than during the execution of maneuvers. This means that while drivers may decide to pass more confidently with eHMI, they still rely heavily on kinematic cues to verify their decisions. This emphasises the need for kinematic communication even when eHMI is present. Drivers still feel compelled to verify the behaviours of approaching vehicles independently, thereby limiting the significant improvement of PITs by eHMI. Although some participants reported that the eHMI may have created more uncertainty, most participants stated that eHMI helped them understand the intentions of the AV, and proceed with more confidence in passing decision-making. These results indicate that the vehicle's lateral movement was a strong indicator of its intent, with the added messages from an eHMI possibly causing some confusion if this accompanied the lateral movement, but being useful in the absence of this kinematic cue. These results confirm the importance of using intuitive kinematic behaviour for AVs to communicate intention (Lee et al., 2021), also supporting the suggestion that these can be a better solution than potentially misleading externally presented messages (Kaleefathullah et al., 2020). eHMI should be further evaluated in more complex and uncertain scenarios, including those involving multiple vehicles behind the approaching vehicle, and adverse weather conditions with poor visibility, where the potential benefits of eHMIs may be particularly pronounced.

In terms of limitations, our study focused on a simplistic and ideal driving scenario, a bottleneck scenario with only two moving agents, to analyze the impact of the approaching vehicles' kinematics without any external influences. However, real road traffic scenarios are often more complex, influenced by diverse road layouts and the presence of other road users. Youssef et al., 2024 showed that environmental factors, such as the presence of other road users influence human drivers' likelihood of yielding. Indeed, during the interviews, participants in our study suggested that their decisions and subjective feelings would be influenced by the presence and types of other vehicles behind them, and also those following the approaching vehicles, as well as the broader traffic context, including the presence of pedestrians or cyclists. Weather conditions and whether it was day or night were also mentioned as factors that might have influenced the passing behaviour of our participants. In addition, it is important to take the more complex traffic scenarios with ambiguous right-of-way, such as junction roads without traffic lights (Imbsweiler et al., 2018; Imbsweiler et al., 2018) and shared spaces (Li et al., 2021) into account, to understand if lateral deviation and eHMI still have the same impacts on drivers' decision-making. Moreover, some other eHMIs have been reported (Dey et al., 2020), such as anthropomorphic cues, traffic symbols or even auditory eHMI, and more research is needed to understand if the use of different eHMIs may also lead to different driving decisions. Finally, it should be noted that this experiment was conducted on a static driving simulator, therefore, more research is needed to understand whether similar results would emerge in a real-world scenario, where the participants feel greater risk, and may drive more cautiously.

5. Conclusion

This study highlights the critical role of kinematic cues, particularly lateral offsets, in enhancing drivers' understanding of an approaching vehicle's yielding and non-yielding intentions. The potential benefits of an eHMI are linked to the clarity of the kinematics. If kinematic cues are unambiguous, for example, approaching AV yields with an away offset, the benefits of eHMIs are limited. Thus, designers should consider how eHMIs can provide additional information where kinematic cues are not possible. These insights can guide the future design of AVs and contribute to safer and more reliable interactions between AVs and MV drivers in bottleneck scenarios. Furthermore, our driving simulator study shows that knowing whether the approaching vehicle is an AV or MV does not impact driver performance; instead, the kinematics of the vehicle are the key factors influencing drivers' decision-making.

CRediT authorship contribution statement

Li Yang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Yee Mun Lee:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Ruth Madigan:** Writing – review & editing, Visualization, Validation, Supervision. **Armin Grunwald:** Writing – review & editing. **Barbara Deml:** Writing – review & editing, Funding acquisition. **Natasha Merat:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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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Data availability

Data will be made available on request.

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