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Influence of surrounding traffic on lane change dynamics: Insights from a video-based laboratory study

Sarang Jokhio [a,*], Marco Dürr [a], Jonas Bärgman [b], Martin Baumann [a]

[a] Department of Human Factors, Institute of Psychology and Education, Ulm University, 89081, Ulm, Germany

[b] Division of Vehicle Safety, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, 412 96, Gothenburg, Sweden

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ABSTRACT

The inherent complexity associated with lane-changing manoeuvres can significantly disrupt traffic flow and increase the risk of collisions. While the lane-changing vehicle influences the surrounding traffic, it is also simultaneously influenced by it. This study aims to examine how the presence and behaviour of surrounding vehicles affect the lane changer's behaviour. A study was conducted in the laboratory using video stimuli of various simulated lane-changing scenarios to achieve the research aim. The study used a two-block design. In the first block, the impact of the lag vehicle was evaluated by varying its gap and behaviour (acceleration, deceleration or maintaining speed) relative to the lane-changing vehicle. In the second block, both the lead and lag gaps were manipulated with respect to the lane-changing vehicle. Data from the participants (n = 29) were collected on dependent variables, including lane change decisions (gap acceptance or rejection), perceived cooperation, and reaction time. The analysis was conducted using an Aligned Rank Transform ANOVA. The findings of this laboratory-based study suggest that the lag vehicle, specifically its behaviour, has more influence on lane change decisions than the lead vehicle in the target lane. Additionally, when a lag vehicle decelerates to create a gap in response to a lane changer's request, its actions are perceived as more cooperative, compared to when it accelerates or maintains speed. Furthermore, decisions to change lanes are made faster when the lag vehicle shows a deceleration behaviour. The results of this laboratory-based study provide valuable insights for improving current lane-changing models. We also discuss the implications of findings for improving algorithms governing autonomous vehicle interactions in mixed traffic. Finally, we discuss the benefits and limitations of laboratory-based approaches in studying causal relationships among different factors, as well as the generalizability of our findings.

1. Introduction

The traffic on highways is mostly influenced by car following and lane-changing principles. In a car-following situation, drivers maintain safe distances from vehicles ahead, adjusting speed and distance according to changes in traffic flow. Lane changing, on the other hand, is the act of strategically maneuvering from one lane to another to overtake slower vehicles (discretionary lane change), avoid a lane blockage further ahead, and prepare for a turn or exit from the highway (mandatory lane change).

* Corresponding author.
E-mail address: sarang.jokhio@uni-ulm.de (S. Jokhio).

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The lane changing is generally more complex than car following. Lane changing is not just a reactive maneuver like car following, but often a strategic decision based on multiple factors and requiring evaluation of conditions in multiple lanes. Due to the inherent complexity, lane changing can significantly disrupt traffic flow (Laval & Daganzo, 2006) and create the potential for collisions (Li & Sun, 2017). Therefore, an improved understanding of factors affecting lane changing would allow us to create and or improve current lane-changing models. Lane-changing simulation models are also crucial for studying the impact of human-driven vehicles (HDVs) on autonomous vehicles (AVs) and vice versa in a mixed-traffic environment.

One of the factors that impact lane change behaviour is the presence and behaviour of surrounding vehicles. For instance, a slow-moving vehicle in the current lane (referred to as the front vehicle) could trigger a lane change. This type of lane change is referred to as discretionary lane change (Balal et al., 2014). While the presence of a slow-moving front vehicle triggers a lane change, the actual execution heavily depends upon vehicles in the target lane (referred to as lead and lag vehicles). The existing research shows that vehicles in the target lane impact the lane-changing vehicle (Moridpour et al., 2010; Long et al., 2020; Yan et al., 2015; Jokhio et al., 2023). During a typical lane change (e.g. a discretionary lane change), a driver sends a 'courtesy' request to lag the vehicle in the target lane through the turn indicator (Hidas, 2002). The request is either accepted or rejected, resulting in cooperative or non-cooperative behaviour of lag vehicles respectively (Hidas, 2002; Kauffmann et al., 2018; Stoll et al., 2020). Lag vehicle drivers can signal their intent by adjusting their speed, such as decelerating to create a gap, facilitating the lane change for the other driver. For example, in a simulator study by Kauffmann et al. (2018) showed that lag vehicle drivers prefer an early lane change indication and are willing to cooperate in this situation. In most cooperative situations, the preferred behaviour of lag vehicle drivers is deceleration when responding to lane change requests (Stoll et al., 2020). This cooperative behaviour is also affected by situation criticality where drivers show more willingness to cooperate (Stoll et al., 2019, 2020).

Most of the studies referred to above focused on the perspective of lag vehicle drivers. However, it is important to consider the perspective of lane-changing drivers, which is often overlooked. Several studies have indicated that the presence of surrounding vehicles leads to uncertainty in lane change decision-making (Yan et al., 2015, 2023). Uncertainty here is the challenge of deciding to change lanes or not in a given situation (Yan et al., 2023). Specifically, factors such as distance gap (between ego and lag vehicle), time-to-collision (TTC) and closing velocity were influential in predicting uncertainty in decision-making (Yan et al., 2023). In situations with higher uncertainty, the reaction time to decide on changing lanes after a stimulus was also found to be longer (Yan et al., 2023).

In the following paragraphs, the word 'decision' or 'decision-making' refers to the acceptance or rejection of certain gaps in a lane change scenario. Studies by Yan et al. (2015, 2023) showed that the size of the lag gap does influence lane change decisions. On the other hand, results from Long et al. (2020) indicate that it is primarily the leading vehicle that impacts lane-changing decisions. It is also unclear how the gaps between the lane-changing vehicle and lead and lag vehicles influence the decision-making process when changing lanes. In most existing studies, the lag gap is primarily varied. Furthermore, in Yan et al. (2015, 2023), only closing velocity (that is acceleration) was manipulated. However, the impact of varying behavioural responses from the lag vehicle (e.g. deceleration, maintaining speed, acceleration), which dynamically alters the gap size, remains unexplored.

Previous studies also show that drivers typically wait a few seconds after indicating and before starting the lane change (Jokhio et al., 2023). This waiting time suggests that an adequate gap may not be immediately available when deciding to change lanes. While the actual decision-making process is inherently latent, it can be inferred from the activation of the turn signal. The waiting time (after starting the turn signal and before starting lane change) is also affected by the presence and gap to lag and lead vehicle (Jokhio et al., 2023). In this case, a lag vehicle can help lane-change execution by, for example, reducing its speed and creating a space (Kauffmann et al., 2018; Stoll et al., 2020).

1.1. Current study

It remains unclear whether and how a driver intending to change lanes takes into account behaviour from lag vehicles during their lane-changing decision process. As mentioned earlier, drivers of lag vehicles may create space (e.g., by deceleration) for those changing lanes, which is known as cooperative behaviour. It remains unclear whether drivers making a lane change perceive this as cooperative and if this perceived cooperation influences their decision-making process. Therefore, this laboratory-based study aims to investigate the impact of surrounding vehicles on lane change decision-making.

Overall, this study is divided into two blocks. In the first block, only the impact of the lag vehicle is measured by varying lag gap sizes and behaviour. One central focus is examining the role of the lag gap in drivers' decisions. We aim to understand whether larger lag gaps, which may provide a higher certainty (Yan et al., 2015, 2023), lead to more frequent lane changes. Additionally, how the lag vehicle's behaviour (e.g. decelerating) impacts the decision regarding lane changes. Moreover, we also aim to explore which behaviour of lag vehicles is perceived as cooperative or not. This would provide deeper insights into the drivers' perspectives and how they affect their decision-making in lane changing. Lastly, we want to explore which behaviour of the lag vehicle increases or decreases the reaction time in the decision-making process of a lane change (e.g. acceptance or rejection of a gap).

While in the second block, the lead and lag gaps are varied concerning the lane-changing vehicle. Here, we aim to explore how different distance ratios between vehicles affect a driver's decision to change lanes. The second block shifts from an isolated perspective (involving just the lag and lane-changing vehicles) to a broader perspective by simultaneously considering the distances to both the lead and lag vehicles in the target lane. The findings from the second block could provide insight into whether drivers changing lanes take into account both the gap between the lag and lead vehicle.

Fig. 1. Simulator mockup used in the study.

2. Method

2.1. Participants

We recruited 29 participants (18 female, 11 male) through the university's test management system, mailing lists, and student WhatsApp groups. The participants were between 18 and 79 years old, with a mean age of 38 and a standard deviation of 19 years. All participants possessed a valid German driving license for a minimum of Class B, which allows them to operate passenger cars. The participants had driving licenses for 1 to 60 years, with an average of 20.07 years and a standard deviation of 19.13 years. 25 participants held a bachelor's degree or higher, while 4 participants had up to an intermediate school diploma. The majority of the participants were either students (11) or employed (9). The rest included self-employed or retired individuals (9). All participants received compensation, either in the form of money (7.5 euros) or study course credits (0.75 credits), for their time. The course credits were only applicable to the Bachelors student of psychology at Ulm University.

2.2. Equipment

This study was conducted in a laboratory setting using simulated videos of different lane-changing situations. Video-based experiments have become increasingly popular and are now a viable alternative to simulator-based studies (Stoll et al., 2019; Miller et al., 2022). These studies offer a practical approach, often with lower costs and easier setup, while still providing valuable insights that are comparable to those obtained from more complex simulator setups. To increase the level of immersion beyond what is typically achieved in video-based online studies, this research was conducted in a laboratory setting. The experimental setup consisted of a static driving simulator and three 55-inch monitors with a display resolution of 1920 by 1080 each. To increase realism, a mockup, including a steering wheel and a driving seat, was placed in front of the screens, as shown in Fig. 1. The participant's view consisted of the front view of the scenario, three back views functioning as the side and back mirrors and the tachometer. The stimuli videos were produced through SILAB 6.5 driving simulator software (WIVW GmbH, 2023). Participants' reactions were gathered via three buttons attached to the steering wheel of the simulator mockup. To increase immersion, participants were informed that the vehicle detects slower-moving vehicles and signals a feasible lane change with an indicator. However, the final decision to change lanes or not is made by the participant. Before the actual experiment, the participants were presented with videos and a questionnaire to familiarize themselves with the study.

2.3. Study design

Each block in our study used a different experimental design. The first block uses a 3x3 within-subject design with two factors, so each participant experiences every scenario. While in the second block of the study, a one-way within-subjects design is used. The order in which participants encountered the blocks was randomly selected at the start of the experiment to ensure variability and minimize potential biases. Additionally, within each block, the conditions were randomly presented to prevent habituation effects, where repeated exposure might reduce responsiveness to the stimuli. The randomization was applied to both the different conditions and their subsequent repetitions. The scenario in both blocks was chosen to be located on a straight part of a four-lane German highway with two lanes in each direction divided by a barrier. This type of highway was chosen for the scenario since it accounts for approximately two-thirds of the length of the German highway system and is, therefore, the most common highway type in Germany (Federal Ministry of Transport and Digital Infrastructure and Federal Highway Administration, 2022). The participants took the ego perspective of a vehicle in the right lane, travelling at 130 km/h. The participantś vehicle approached a slower lead vehicle in the current lane, travelling at a speed of 100 km/h.

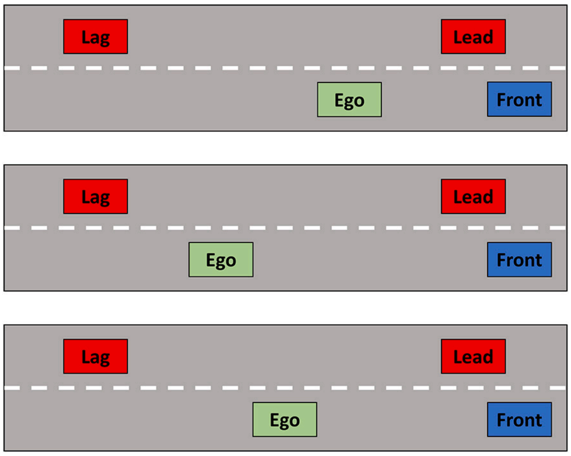


Fig. 2. Scenarios for Block 2: lag gap > lead gap (top); lag gap < lead gap (middle); lag gap = lead gap (bottom).

In the first block, the size of the lag gap (48 m, 36 m, 24 m) and the behaviour of the lag vehicle (acceleration, deceleration, and maintaining speed) were manipulated. The gap to the front (100 m) and lead vehicle (110 m) was kept constant in each scenario. These values were obtained from Long et al. (2020), who reported that, at these values, a lane change becomes highly likely. The values for the lag gap size were chosen from Yan et al. (2015), who reported that the participants had a clear preference for a lane change at these values. The acceleration and deceleration conditions were set to $\pm 2, m/s^2$ (Bokare & Maurya, 2017; Wang et al., 2019). The gap between the lag and lane-changing vehicles was measured when the lane-changing vehicles (i.e., ego vehicles) activated the turn signal. Depending on the lag vehicle behaviour, this gap increased (deceleration), decreased quickly (acceleration) or decreased slowly (maintaining speed). The two variables (lag gap size and lag vehicle behaviour) were paired in every possible combination, resulting in nine conditions. Each condition was randomly presented to the participants six times during the experiment. The distances to the front (lead vehicle in current lane) and lead vehicle (target lane) were kept the same and constant in each condition.

In the second block, the gap between lead and ego and lag and ego vehicle is varied, as shown in the Fig. 2. In condition one (top figure), a bigger lag gap and smaller lead gap are available at the time when the video stops. In the second condition (middle figure), a bigger lead gap and a smaller lag gap are available when the video stops. While in the third condition, equal lead and lag gaps are available at the time when the video stops. The gap between the lead and lag vehicle is kept constant (Approximately 160 meters or 4 seconds in time gap) in all three conditions. The ego vehicle was driving at 130 km/h, while lead and lag vehicles were travelling at 140 km/h. The selected speeds reflect actual conditions (average speeds) on German highways (Autobahn), where in most parts there are no general speed limits (Löhe, 2016). Each condition was randomly presented to participants 20 times, which resulted in 60 responses per participant.

After participants signed the informed consent, they received instructions about the experimental task. In each condition, the participant observed their vehicle driving on a straight part of the highway, approaching the slower lead vehicle. When the ego vehicle reached predefined distances from the surrounding vehicles, the left indicator activated automatically. The participants were instructed to decide to initiate lane change by pressing either of the two buttons on the keyboard. Pressing the leftmost button would mean that participants want to perform a lane change, while the rightmost button implied not performing a lane change. The reaction time was then calculated between the stopping of the video and the moment participants pressed the button. Additionally, in block 1, the participants were asked to self-report the perceived cooperative behaviour of the lag vehicle. Participants could choose from three options: 'yes,' 'no,' or 'not sure' by pressing any of the three buttons on the keyboard. The next trial appeared as soon as participants responded to the self-report questionnaire. Following the experimental part, the participants filled questionnaire regarding the demographics. The experiment lasted for a total of approximately 45 minutes. It is important to note that, none of the participants reported simulator sickness. This may be because the participants did not experience any lateral motion such as turning, road curvature, or lane change (Klüver et al., 2015). The videos were stopped before any lane change was initiated.

3. Data analysis

In this section, the details regarding the data preparation and the data analysis are presented. During the data-cleaning process, 136 (out of 1566) trials were removed due to outliers in the reaction time from block one. Furthermore, 232 trials were removed from block two. Lower and upper cutoffs were defined to find the outliers in reaction times. The lower cutoff was set to be at least 100 milliseconds (ms), which is the time needed for physiological processes such as stimulus perception and motor responses (Luce, 1986; Whelan, 2008). The upper boundary was determined by figuring out the longest time a participant could take to respond to the driving situation before a collision with the lead vehicle in the current lane became inevitable. It is important to note that there were no observed collisions during the simulation runs as the videos were stopped before a lane change was initiated. We set the upper limit of reaction time to 6000 ms. This was compared to the value obtained through the empirical approach discussed in Whelan (2008), which gave an approximate value of 5534.13 ms. Following this, the data was encoded and aggregated on the participant and condition level. The purpose of the step was to convert decisions to initiate lane change (binary) and perceived cooperation (multinomial) into continuous variables. In this step, we calculated the overall percentage of "Yes" responses from all valid repetitions. For reaction time, the mean was computed across all valid repetitions. The valid repetitions refer to the observations for each subject under specific conditions after removing outliers.

The dependent variables for block one are; lane change decision, reaction time, and perceived cooperation. While in block two, only the lane change decision is considered. The repeated measures analysis of variance (ANOVA) is widely used when the same subjects are measured multiple times in repeated measure designs (Keselman et al., 2001). Given the small sample size, it is important to validate the assumptions of sphericity and normal distribution to ensure the appropriateness of the chosen analysis method. Mauchly's test of sphericity (Mauchly, 1940) and Shapiro-Wilk normality test (Shapiro & Wilk, 1965) showed that all dependent variables violated these assumptions in blocks one and two.

To analyze the data we used the non-parametric Aligned Rank Transformation (ART) ANOVA method (Wobbrock et al., 2011). The ART method allows ANOVA-type procedures to be reliably applied to aligned ranks for analyzing both main effects and interactions without increasing the risk of Type I errors (Elkin et al., 2021). The ART involves two steps: alignment and ranking. The alignment step involves adjusting the data based on the marginal means of the factors, which aligns the data in a way that allows for the interaction to be analyzed. The ranking step involves ranking the aligned data, which makes the data nonparametric. Once the data have been aligned and ranked, a standard ANOVA can be performed on the ranked data (Wobbrock et al., 2011). The ART ANOVA was implemented using 'art' function of 'ARTool' package of R programming language (Elkin et al., 2021). The ART model is given by equation (1).

$$\text{art}(\text{Dependent Variable}) \sim \text{Predictor 1} * \text{Predictor 2} + (1|\text{Subject Number}) \tag{1}$$

Following the ART transformation, an ANOVA was applied to the aligned ranks to identify significant main effects and interactions. The Aligned Rank Transform Contrasts (ART-C) with Holm-Bonferroni corrections were used to conduct post hoc pairwise comparisons (Elkin et al., 2021).

4. Results

The following sections provide the results of block one concerning the dependent variables, followed by the results of block two. For a more detailed summary, please refer to the supplementary materials where ART ANOVA and post hoc test results are provided. It is important to note that the statistical analyses presented herein are based on the ART method, which applies ANOVA to rank transformed data rather than raw data. This approach ensures the validity of statistical tests despite non-normal distributions of data but requires careful interpretation as the results reflect differences in ranks rather than actual values. Additionally, we provide graphical representations of the raw data to show trends and interactions. The consistency of the trends observed in both the rank-transformed and raw data indicates that the findings are reliable, despite the differences in the magnitude and scale of the two types of data representation.

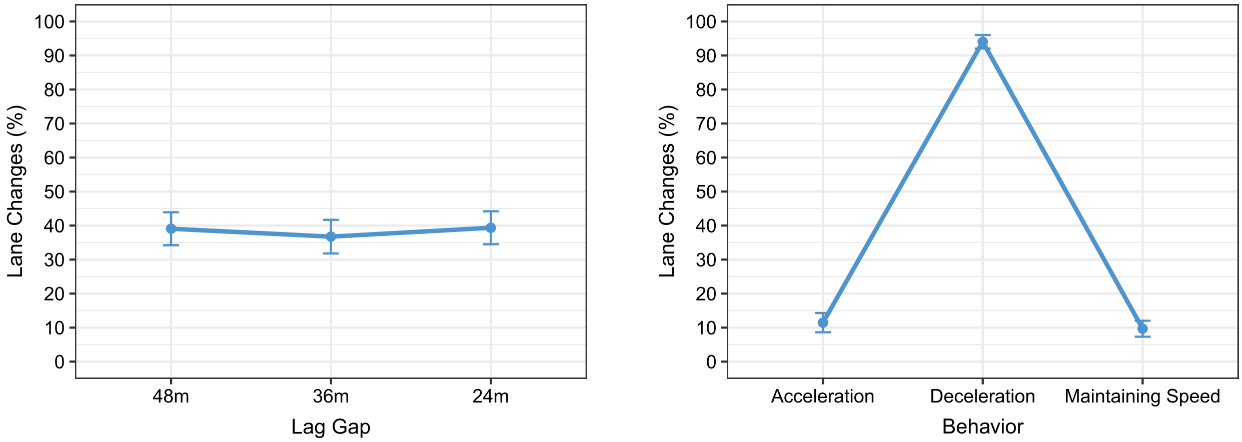
4.1. Lane changes

As previously described, an ART ANOVA was conducted to analyze the effects of lag gap size and behaviour on the decision to lane change. The results showed that the lag gap size does not have a significant effect on the decision to lane change ($F(2, 224) = 2.21$, $p = 0.1119$). However, the results showed a significant main effect of lag vehicle behaviour on the decision to lane change ($F(2, 224) = 243.63$, $p < .0001$). The post-hoc test with 'holm' method showed a significant difference between acceleration and deceleration conditions, with the latter having more lane changes ($t = -19.421$, $p < 0.001$). Likewise, we also found a significant difference between deceleration and maintaining speed conditions, with the former having more lane changes ($t = 18.79$, $p < 0.001$). Fig. 3 shows the mean scores across conditions with associated error bars.

The results of ART ANOVA also showed a significant interaction effect between lag gap and lag vehicle behaviour on the frequency of lane changes ($F(4,224) = 4.84$, $p = .0009$). As shown in Fig. 4, for all three gap sizes, the deceleration behaviour of the lag vehicle was significantly different from acceleration and maintaining speed conditions. For 48 m condition, the lane change frequency significantly decreases when the lag vehicle accelerated compared to when it decelerated ($t = -13.83$, $p < .0001$) and maintained speed ($t = -3.25$, $p = .023$). A significant difference was also observed between acceleration and deceleration ($t = -14.08$, $p < .0001$) and deceleration and maintaining speed ($t = 14.53$, $p < .0001$) while no significant difference was observed between acceleration and maintaining speed ($t = 0.457$, $p = 1.0$) in 36 m gap condition. Similarly for 24 m gap condition, a significant difference was found between acceleration and deceleration ($t = -10.25$, $p < .0001$), acceleration and maintaining speed ($t = 2.92$, $p = 0.048$) as well as deceleration and maintaining speed ($t = -13.18$, $p < .0001$).

The results also show the significant differences in lane changes across the lag gap for the same behaviour. There was a significant increase in the lane changes when comparing acceleration at a 24 m gap to acceleration at a 48 m gap ($t = 3.18$, $p = .028$). In contrast, there was a significant decrease in the lane changes when comparing maintaining speed at a 24 m gap to comparing maintaining speed at a 48 m gap ($t = -2.99$, $p = .042$). However, no significant difference in lane changes was found in lane changes for deceleration across lag gap size.

The results of ART ANOVA showed a significant effect ($F(2, 224) = 5.16$, $p = 0.0064$) of the lag gap size on perceived cooperation. The post-hoc tests with the holm method only showed a significant difference between 36 m and 24 m gap condition ($t = -3.21$, $p = 0.0045$). The results also showed a significant effect of the lag vehicle behaviour on perceived cooperation ($F(2, 224) = 5.16$,



(a) Main effect of lag gap size

(b) Main effect of lag vehicle behavior

Fig. 3. Lane changes: (a) by lag gap and (b) by lag vehicle behaviour. The error bars represent ± standard error of mean (SEM).

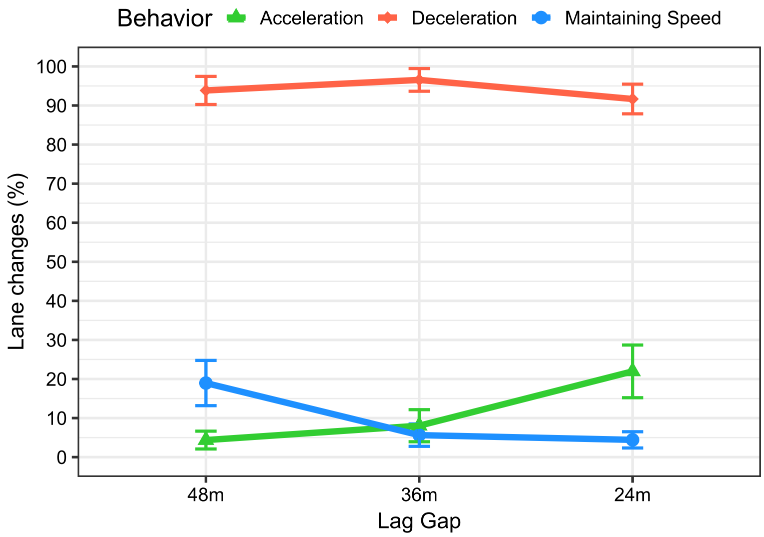


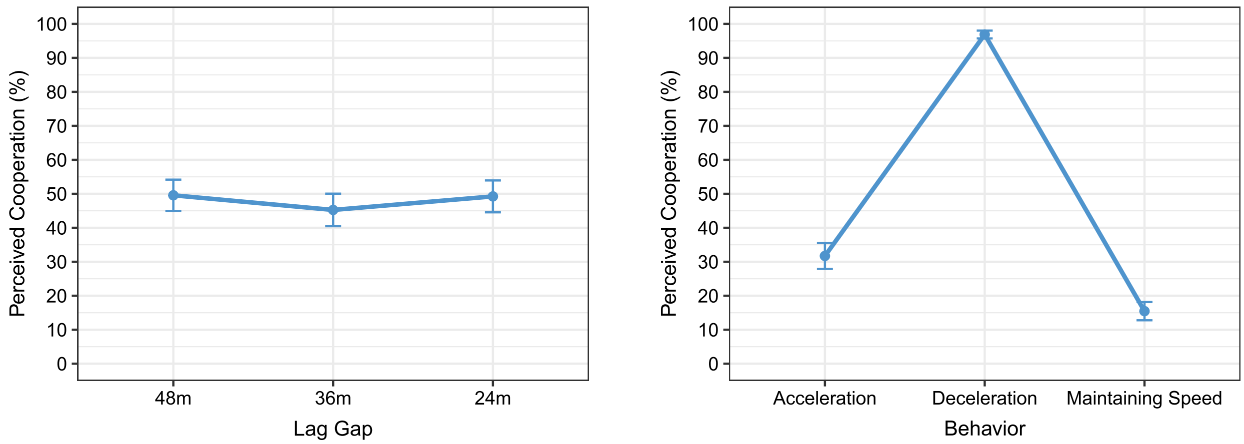
Fig. 4. Interaction effect between lag gap and lag vehicle behaviour on lane changes. The error bars represent ± standard error of mean (SEM).

p <.0001). As expected, the post-hoc test showed that acceleration was perceived as significantly less cooperative compared to deceleration (t = -16.62, p < .0001). In contrast, acceleration was perceived as significantly more cooperative compared to maintaining speed (t = 4.117, p = 0.0001)). Likewise, deceleration was perceived as significantly more cooperative compared to maintaining speed (t = 20.74, p < .0001). The mean scores for perceived cooperation for each condition are shown in Fig. 5.

Regarding the interaction effect between the lag gap and lag vehicle behaviour on perceived cooperation, the ART ANOVA showed a significant difference ($F(4, 224) = 3.15$, $p = 0.0151$). The post-hoc tests showed only significant difference between acceleration and deceleration (t = -10.39, p < .0001)) as well as deceleration and maintaining speed, for 48 m condition (t = 10.96, p < .0001)). Similarly, for the 36 m condition, the significant difference was only observed between acceleration and deceleration (t = -11.17, p < .0001)) as well as deceleration and maintaining speed (t = 13.37, p < .0001)). However, for 24 m condition, the significant difference was observed for all three pairs of behaviour, acceleration and deceleration (t = -8.70, p < .0001)), acceleration and maintaining speed (t = 3.85, p < .0001)) as well as deceleration and maintaining speed (t = 12.56, p < .0001)). The results did not show significant differences in perceived cooperation across the lag gap for the same behaviour. The mean scores are shown in Fig. 6.

4.2. Reaction times

The results of the ART ANOVA did not show a significant effect of lag gap ($F(2, 224) = 0.13$, $p = 0.871$). However, it did show a significant impact of behaviour on reaction time ($F(2, 224) = 18.35$, p < .0001). The post-hoc test shows that reaction time was significantly different in acceleration and deceleration (t = 5.14, p < .0001) as well as deceleration and maintaining speed conditions (t = -5.34, p < .0001). There was no significant difference between acceleration and maintaining speed conditions (t = -0.204, p = .838). The mean scores are shown in Fig. 7.



(a) Main effect of lag gap size

(b) Main effect of lag vehicle behavior

Fig. 5. Perceived cooperation based on (a) By lag gap and (b) By lag vehicle behaviour. The error bars represent ± standard error of mean (SEM).

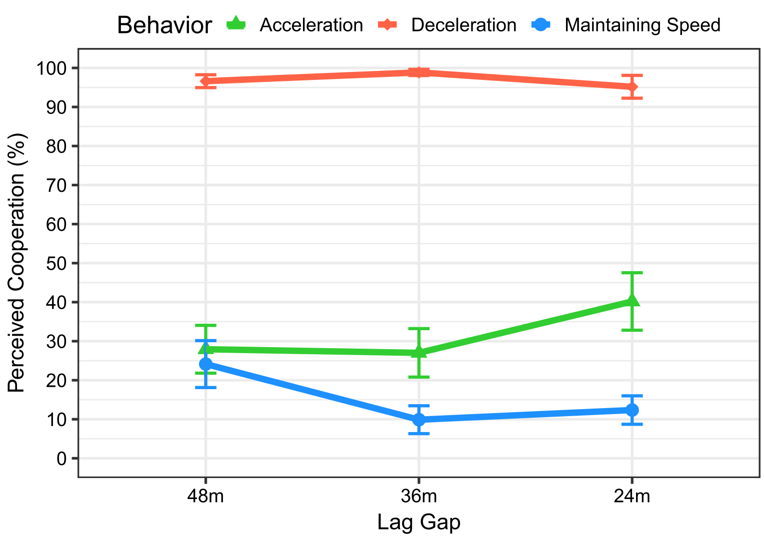
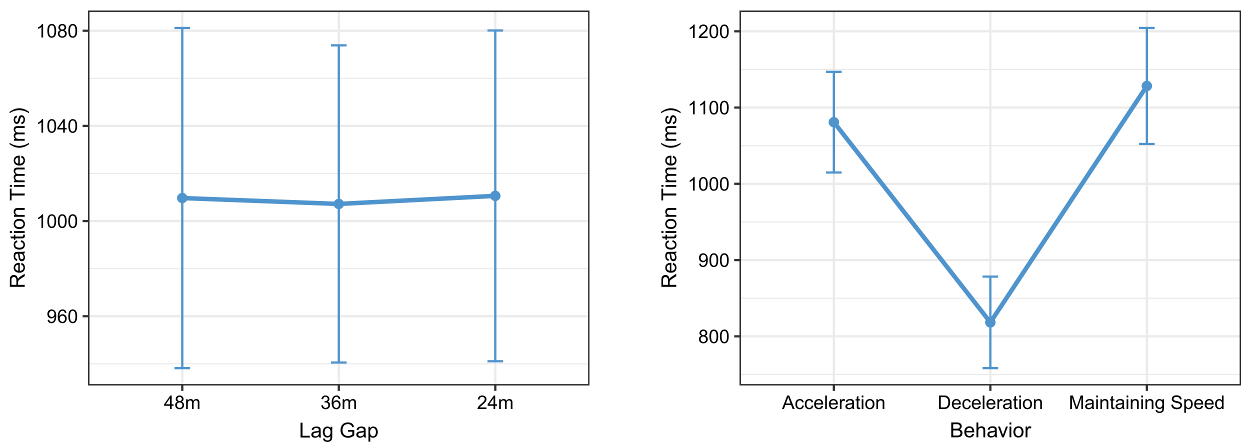


Fig. 6. Interaction effect between lag gap and lag vehicle behaviour on perceived cooperation. The error bars represent ± standard error of mean (SEM).



(a) Reaction time by lag gap size

(b) Reaction time by lag vehicle behaviour

Fig. 7. Reaction time based on different factors. (a) By lag gap size. (b) By lag vehicle behaviour. The error bars represent ± standard error of mean (SEM).

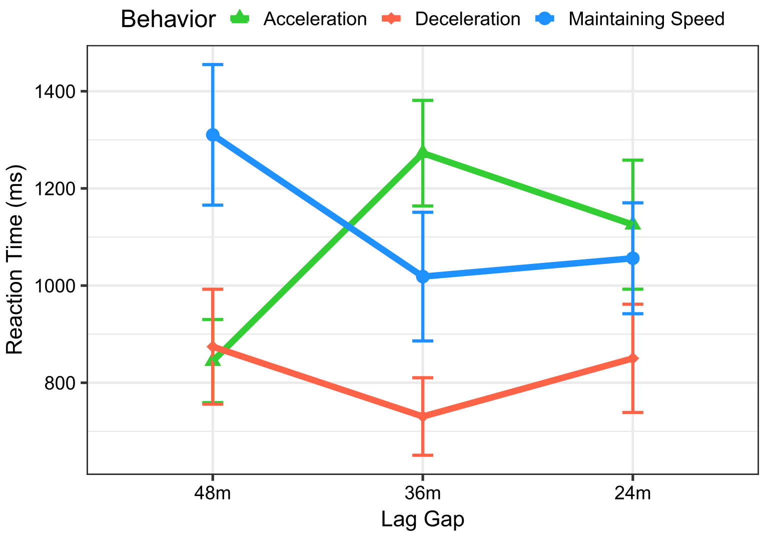


Fig. 8. Interaction effect between lag gap and lag vehicle behaviour on reaction time. The error bars represent ± standard error of mean (SEM).

The ART ANOVA also showed a significant interaction effect between the lag gap and behaviour on reaction time ($F(4, 224) = 7.28$, $p < .001$). The post-hoc tests showed no significant difference between acceleration and deceleration in the 48 m condition ($t = 0.33$, $p = 1.00$). However, a significant difference was observed in reaction time between acceleration and maintaining speed ($t = -3.82$, $p = 0.0049$) as well as deceleration and maintaining speed in the 48 m condition ($t = -4.16$, $p = 0.0014$). For the 36 m condition, a significant difference was only found between acceleration and deceleration ($t = 5.59$, $p < .0001$) as well as acceleration and maintaining speed conditions ($t = 3.16$, $p = 0.046$). For the 24 m condition, no significant differences were observed between any levels of behaviour. Similarly, the results did show significant differences in reaction across the lag gap for the same behaviour. The mean scores are shown in Fig. 8.

4.3. Second block: lane changes

The objective was to determine which of the vehicles in the target lane has more impact on lane change decision-making. In block two, we kept the speed of the lead and lag vehicles constant to create a scenario in which the gap between these remains constant. Hence, only the gap was varied when the video stopped, resulting in either a big lead or lag gap in conditions one and two and an equal gap in condition three. The analysis was also conducted using ART ANOVA. The results showed a significant effect of varying gaps on the frequency of lane changes ($F(2, 56) = 88.96$, $p < .0001$). The post-hoc tests showed that significantly more lane changes were performed in case of a big lag gap compared to a big lead gap ($t = 13.21$, $p < .0001$) and equal gap ($t = 5.62$, $p < .0001$). Furthermore, significantly more ($t = -7.59$, $p < .0001$) lane changes were performed in case of an equal gap compared to a big lead gap. Fig. 9 shows the mean scores across conditions with associated error bars.

5. Discussion

This section provides a detailed discussion of findings about existing literature and their implications. This laboratory-based study was divided into two blocks. In the first block, a 3x3 within-subject design was adopted. The impact of lag gap and lag vehicle behaviour was studied on the decision to lane change, perceived cooperation and reaction time. The second block investigated the influence of varying distance ratios between vehicles in the target lane on a driver's lane change decision only.

5.1. Lane changes

Contrary to our expectations, the results did not show a significant effect of the gap on lane change decisions. These results do not align with the findings of Yan et al. (2023) who showed that gap size affects decision-making. They found that larger gaps resulted in more frequent lane changes compared to smaller gaps. Additionally, they showed that medium gap sizes (36 to 44 m) may induce uncertainty in drivers' decision-making. This uncertainty, as Yan et al. (2023) suggests, results from the ambiguity of medium gaps, which are neither clearly safe nor too tight for a lane change. This uncertainty could lead to different behaviours among drivers.

The results further indicated that regardless of initial gap sizes, lane changes (or acceptance of gap) increased when the lag vehicle showed a clear deceleration behaviour compared to acceleration and maintaining speed. This finding suggests that drivers interpret the deceleration of the lag vehicle as a clear sign of yielding, making them more confident and likely to initiate a lane change. On the other hand, maintaining speed conditions resulted in fewer lane changes (except at 48 m gaps) than acceleration and deceleration. This suggests that the lag vehicle's appropriate behavioural response can assist the lane changer in deciding whether to change lanes or not. Not responding to a lane changer's request (e.g. to turn the signal) could create an ambiguous situation for the changer.

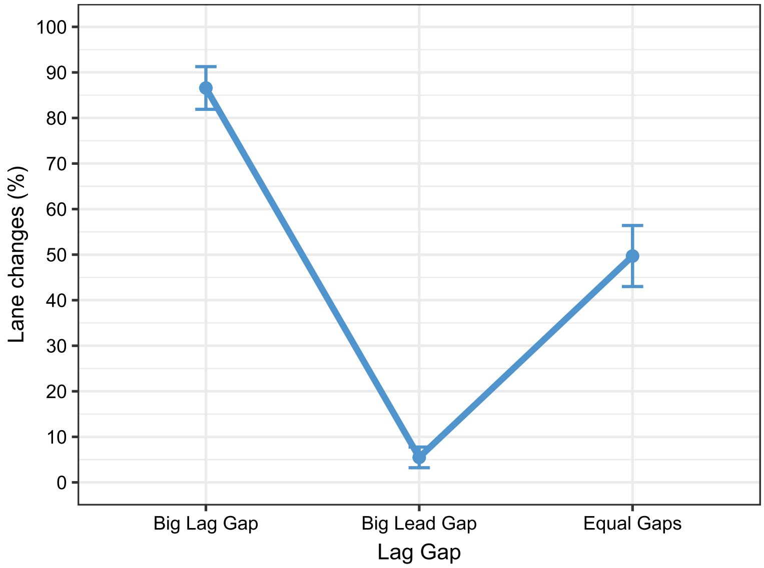


Fig. 9. Lane changes by varying gap sizes. The error bars represent ± standard error of mean (SEM).

The results also showed a significant interaction effect between lag gap size and lag vehicle behaviour. The frequency of lane changes increased when the lag vehicle showed a clear deceleration behaviour at all lag gap sizes. In each, scenario, the deceleration increased the gap size, resulting in a certain gain in safety. According to Long et al. (2020), this gain in safety would increase the possibility of lane change. The acceleration resulted in more lane changes at 24 m gap sizes than maintaining speed. In a condition with a 24 m initial gap size, when the lag vehicle accelerated, it crossed the changing vehicle and created a small lead gap behind it. In this condition, the lag vehicle became the lead vehicle in the target lane. This could explain the increased frequency of lane changes compared to maintaining speed, even though the resulting lead gap was smaller. This behaviour is further explained by the results of block two, which is discussed in detail later in this section. In contrast, the results showed that maintaining speed conditions resulted in significantly more lane changes than acceleration at a bigger (48 m) lag gap size. This indicates that drivers prefer lag gaps that are equal to or larger than 48 m (or approximately 1.2 seconds) when lag vehicles show no clear behaviour.

5.2. Perceived cooperation

Current literature suggests that lag vehicle drivers consider decelerating, to allow the lane changer to merge, as cooperative behaviour (Heesen et al., 2012; Stoll et al., 2020). Acceleration can also be considered cooperative, but it is highly dependent on the context (if accelerating the vehicle creates a gap behind it) (Stoll et al., 2020). However, existing studies only focused on the perspective of a lag vehicle driver (one who is cooperating to create a gap). Therefore, in this study, we investigated which behaviour of the lag vehicle is considered cooperative by the lane-changing driver (one who is requesting cooperation). The participants responded to the behaviour as cooperative, non-cooperative or not sure. The results showed that participants, having the perspective of a lane-changing driver, perceived deceleration as cooperative behaviour in all lag gap sizes. As previous studies have shown, deceleration is a clear indication of yielding or creating a gap; hence, it is considered as cooperative behaviour. However, acceleration could also be interpreted as cooperative behaviour in situations with smaller initial gaps. In this situation, the accelerating lag vehicle might create a gap behind it which lane changing vehicle can use; hence, this behaviour could be interpreted as cooperative as well (Stoll et al., 2020). Further research is needed to explore the impact of acceleration on perceived cooperation, ideally with the dynamic interaction scenarios in the driving simulator.

5.3. Reaction time

We expected a lower reaction time in conditions with clear behaviour (e.g. deceleration or acceleration), irrespective of the decision (e.g., acceptance or rejection of the gap). However, the results showed a significantly lower reaction time in deceleration conditions than in acceleration and maintaining speed. The higher reaction times in acceleration conditions could be explained by increased uncertainty (Yan et al., 2015). Yan et al. (2015, 2023) provides insights into driver uncertainty during the decision-making process, with longer reaction times reflecting increased uncertainty in lane-change decisions. The acceleration closes the lag gap, and it might be difficult for the driver to predict the trajectory given the small to medium gap. On the other hand, the deceleration is a clear indication of yielding (in this case, creating a gap), which increases certainty; hence, it is also associated with lower reaction time. Contrary to our expectation, no significant difference in acceleration versus maintaining speed conditions existed.

5.4. Second block: lane changes

The decision to change lanes is affected not only by the lag vehicle but may also be affected by the presence of a lead vehicle. The second block aimed to investigate how the presence of lead and lag vehicles impacted lane change decisions. We kept the speed of lead and lag vehicles the same to maintain a constant gap between them. By doing this, we created three situations, as shown in Fig. 2. When the video stopped, one of three conditions was presented: a large lead gap with a small lag gap (Condition 1), a large lag gap with a small lead gap (Condition 2), or equal lead and lag gaps (Condition 3). The results indicated that the frequency of lane changes was higher in situations with large lag gaps than with large lead and equal gaps. The frequency of lane changes was also higher in situations with equal gaps than higher lead gaps. This suggests that the lag gap is more dominant in influencing lane change decisions than the lead gap. These results align with, for example, studies by Yan et al. (2015, 2023). However, our findings are in contrast with the findings of Das et al. (2020). Their findings suggested that drivers tend to give more importance to lead gaps than to lag gaps when making lane-changing decisions. One possible reason for this discrepancy could be the difference in data collection methods. It is important to note that, Das et al. (2020) used naturalistic driving data, while our study collected data in a controlled laboratory environment. In naturalistic settings, drivers are influenced by various external factors that were not accounted for in our laboratory-based approach.

5.5. Implications

The findings of this study have several implications for improving existing lane-changing models and improving algorithms of AV interaction in mixed traffic situations.

Current lane change models can be calibrated to consider the behavioural responses of lag vehicles for more accurate predictions. Existing models also do not account for reaction time as a variable that can be influenced by other factors. Given the variability in human behaviour, reaction time can be modelled probabilistically, drawing from empirical data to define the distribution of reaction times under various conditions. Our study also provides empirical data to calibrate gap-acceptance or gap-rejection criteria. Our findings provide insights into how lane-changing drivers may perceive the behaviour of lag vehicles (e.g. cooperative or non-cooperative). Subjective variables, like the perception of cooperation, are not commonly incorporated into lane-changing models but could add a layer of realism. Last but not least, our findings suggest complex interactions between the variables (e.g. gap and behaviour) and could guide efforts to include such complexities in future lane-changing models.

In scenarios involving an AV (e.g. SAE Level 3 (SAE International, 2018)), where the human user primarily monitors rather than actively drives, the decision-making process for lane changes becomes especially critical. The findings suggest that participants' preferences for initiating a lane change varied depending on the behaviour of the lag vehicle. For example, the deceleration of the lag vehicle can be viewed as a non-verbal communication signal for yielding (cooperative) and should be interpreted by an AV as such. The decision made by an AV must also align with the preference of its user (i.e. driver). Previous research has shown that aligning individual preferences with AV decisions leads to more positive impressions of the system than when decisions are not aligned (Park et al., 2020). A mismatch between drivers' preferences and AV behaviour may lead to disengagement, especially in partial AVs (Gershon et al., 2021; Nordhoff & De Winter, 2023). An AV should also be able to recognize situations when the surrounding vehicle drivers are cooperating. However, cooperation must be requested by AN using clear communication using turn signal (Kauffmann et al., 2018; Jokhio et al., 2024).

5.6. Limitations

While this laboratory-based study provided valuable insights, it as most driving simulator studies, has limitations in terms of generalizability of the results. Our study aims to investigate the causal relationship between the behaviour of surrounding vehicles (specifically the lag and lead vehicle) and the driver's decision to change lanes. To improve the understanding of this causal relationship, it is crucial to have the highest possible control over the experimental setting, which results in better internal validity (Hock et al., 2018). This can be achieved through laboratory-based simulation studies, which offer a controlled environment where specific conditions can be safely replicated and studied. However, it is important to note that the results of such studies should not be viewed as an absolute reflection of real-world driving scenarios. Therefore, the findings of simulator studies, like any other study, should always be interpreted with caution, taking into account their specific limitations in scope.

This study was conducted in a laboratory setting; however, pre-recorded videos were used as stimuli. Using pre-recorded videos restricts the ability to replicate the full range of sensory inputs and interactions that occur during actual driving, thereby reducing the level of immersion. Our objective was to examine driver behaviour in specific lane change scenarios. However, if participants had control over the vehicle, it would be difficult to expose them to the precise conditions required for our analysis. Future studies may use driving simulators that provide more dynamic interaction and improved immersion. However, allowing interactions with vehicle control in study designs would likely require substantial adjustments.

For future research on lane change behaviour in the laboratory, whether conducted through video-based or driving simulator studies, it is important to study a larger and more diverse participant pool to ensure the findings can be more broadly generalized. Additionally, further investigation is needed to explore the transferability of results, such as those related to study paradigms affecting immersion. Researchers should also consider using naturalistic driving data to understand how surrounding vehicles affect lane change decision-making. However, implementing these approaches presents considerable challenges, including the complexity of setup and overall cost (Bärgman, 2015). Additionally, due to the uncontrollable nature of real-world settings, it is difficult to isolate the effects of specific variables on driving behaviour, even though naturalistic data possesses high ecological validity. This can lead to a decrease in internal validity, making it impossible to draw any causal conclusions from the results. In summary, this study provides a piece of the puzzle to understand lane change behaviour. However, more research is required using different study paradigms.

6. Conclusion

This study aims to provide insights into how the presence and behaviour of surrounding vehicles affect lane-changing behaviour. To achieve this, we conducted a laboratory-based study to assess the impact of surrounding vehicles on lane changing by varying the gap sizes and the behaviour (particularly of lag vehicles). Overall, the study used a within-subject design in two blocks. Lane change interaction videos were used as stimuli. Participants' responses were collected after each scenario (presented multiple times) to determine the frequency of lane change, reaction time and whether or not the behaviour of the lag vehicle was perceived as cooperative.

Our findings contribute to the growing body of literature on lane-changing behaviour by providing insights into the impact of surrounding vehicles. The results indicate that a lag vehicle more than a lead vehicle affects the overall behaviour. Furthermore, the behaviour of a lag vehicle is perceived as more cooperative when it decelerates to create a gap while responding to a request by the lane changer. Lastly, the decision to change lanes is made faster when the lag vehicle shows a clear deceleration behaviour.

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CRediT authorship contribution statement

Sarang Jokhio: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Dürr:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jonas Bärgman:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Martin Baumann:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

The processed data required to reproduce the above findings are available to download from https://doi.org/10.17605/OSF.IO/J7FYS.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used GPT-4 (ChatGPT) and GrammarlyGO to improve the readability of some sentences. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.trf.2024.06.025.

References

Balal, E., Cheu, R. L., Gyan-Sarkodie, T., & Miramontes, J. (2014). Analysis of discretionary lane changing parameters on freeways. *International Journal of Transportation Science and Technology*, *3*(3), 277–296.

Bärgman, J. (2015). *On the analysis of naturalistic driving data*. Ph.D. thesis, Chalmers Tekniska Hogskola (Sweden).

Bokare, P. S., & Maurya, A. K. (2017). Acceleration-deceleration behaviour of various vehicle types. *Transportation Research Procedia*, *25*, 4733–4749.

Das, A., Khan, M. N., & Ahmed, M. M. (2020). Nonparametric multivariate adaptive regression splines models for investigating lane-changing gap acceptance behavior utilizing strategic highway research program 2 naturalistic driving data. *Transportation Research Record*, *2674*(5), 223–238.

Elkin, L. A., Kay, M., Higgins, J. J., & Wobbrock, J. O. (2021). An aligned rank transform procedure for multifactor contrast tests. In *The 34th annual ACM symposium on user interface software and technology* (pp. 754–768).

Federal Ministry of Transport and Digital Infrastructure and Federal Highway Administration (2022). *Length statistics of interurban roads*.

Gershon, P., Seaman, S., Mehler, B., Reimer, B., & Coughlin, J. (2021). Driver behavior and the use of automation in real-world driving. *Accident Analysis and Prevention*, *158*, Article 106217.
Heesen, M., Baumann, M., Kelsch, J., Nause, D., & Friedrich, M. (2012). Investigation of cooperative driving behaviour during lane change in a multi-driver simulation environment. In *Human factors and ergonomics society (HFES) Europe chapter conference touluse* (pp. 305–318).
Hidas, P. (2002). Modelling lane changing and merging in microscopic traffic simulation. *Transportation Research. Part C, Emerging Technologies*, *10*(5–6), 351–371.
Hock, P., Kraus, J., Babel, F., Walch, M., Rukzio, E., & Baumann, M. (2018). How to design valid simulator studies for investigating user experience in automated driving: Review and hands-on considerations. In *Proceedings of the 10th international conference on automotive user interfaces and interactive vehicular applications* (pp. 105–117).
Jokhio, S., Olleja, P., Bärgman, J., Yan, F., & Baumann, M. (2023). Analysis of time-to-lane-change-initiation using realistic driving data. *IEEE Transactions on Intelligent Transportation Systems*.
Jokhio, S., Olleja, P., Bärgman, J., Yan, F., & Baumann, M. (2024). Exploring turn signal usage patterns in lane changes: A Bayesian hierarchical modelling analysis of realistic driving data. *IET Intelligent Transport Systems*, *18*(2), 393–408.
Kauffmann, N., Winkler, F., Naujoks, F., & Vollrath, M. (2018). "What makes a cooperative driver?" Identifying parameters of implicit and explicit forms of communication in a lane change scenario. *Transportation Research. Part F, Traffic Psychology and Behaviour*, *58*, 1031–1042.
Keselman, H., Algina, J., & Kowalchuk, R. K. (2001). The analysis of repeated measures designs: A review. *British Journal of Mathematical & Statistical Psychology*, *54*(1), 1–20.
Klüver, M., Herrigel, C., Preuß, S., Schöner, H.-P., & Hecht, H. (2015). Comparing the incidence of simulator sickness in five different driving simulators. In *Proceedings of driving simulation conference*.
Laval, J. A., & Daganzo, C. F. (2006). Lane-changing in traffic streams. *Transportation Research. Part B: Methodological*, *40*(3), 251–264.
Li, X., & Sun, J.-Q. (2017). Studies of vehicle lane-changing dynamics and its effect on traffic efficiency, safety and environmental impact. *Physica A: Statistical Mechanics and its Applications*, *467*, 41–58.
Löhe, U. (2016). Geschwindigkeiten auf Bundesautobahnen in den Jahren 2010 bis 2014. Schlussbericht zum AP-Projekt F1100.6213001. Fachveröffentlichung der Bundesanstalt für Straßenwesen.
Long, X., Zhang, L., Liu, S., Wang, J., et al. (2020). Research on decision-making behavior of discretionary lane-changing based on cumulative prospect theory. *Journal of Advanced Transportation*, *2020*.
Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization, Vol. 8*. USA: Oxford University Press.
Mauchly, J. W. (1940). Significance test for sphericity of a normal n-variate distribution. *The Annals of Mathematical Statistics*, *11*(2), 204–209.
Miller, L., Leitner, J., Kraus, J., & Baumann, M. (2022). Implicit intention communication as a design opportunity for automated vehicles: Understanding drivers' interpretation of vehicle trajectory at narrow passages. *Accident Analysis and Prevention*, *173*, Article 106691.
Moridpour, S., Rose, G., & Sarvi, M. (2010). Effect of surrounding traffic characteristics on lane changing behavior. *Journal of Transportation Engineering*, *136*(11), 973–985.
Nordhoff, S., & De Winter, J. (2023). *Why do drivers and automation disengage the automation? Results from a study among Tesla users*.
Park, S. Y., Moore, D. J., & Sirkin, D. (2020). What a driver wants: User preferences in semi-autonomous vehicle decision-making. In *Proceedings of the 2020 CHI conference on human factors in computing systems* (pp. 1–13).
SAE International (2018). *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*. SAE Standard J3016 J3016-201806, Warrendale, PA: SAE International.
Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591–611.
Stoll, T., Müller, F., & Baumann, M. (2019). When cooperation is needed: The effect of spatial and time distance and criticality on willingness to cooperate. *Cognition Technology & Work*, *21*, 21–31.
Stoll, T., Lanzer, M., & Baumann, M. (2020). Situational influencing factors on understanding cooperative actions in automated driving. *Transportation Research. Part F, Traffic Psychology and Behaviour*, *70*, 223–234.
Wang, X., Yang, M., & Hurwitz, D. (2019). Analysis of cut-in behavior based on naturalistic driving data. *Accident Analysis and Prevention*, *124*, 127–137.
Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record*, *58*, 475–482.
WIVW GmbH (2023). Driving simulation and SILAB. Web page, (Accessed 27 May 2023).
Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011). The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 143–146).
Yan, F., Weber, L., & Luedtke, A. (2015). Classifying driver's uncertainty about the distance gap at lane changing for developing trustworthy assistance systems. In *2015 IEEE intelligent vehicles symposium (IV)* (pp. 1276–1281). IEEE.
Yan, F., Eilers, M., & Baumann, M. (2023). Investigating driver uncertainty about lane change decisions. *Transportation Research. Part F, Traffic Psychology and Behaviour*, *95*, 369–379.