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Response times in drivers' gap acceptance decisions during overtaking

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ABSTRACT

Overtaking on two-lane roads can lead to increased collision risks due to drivers' errors in evaluating whether or not to accept the gap to the vehicle in the opposite lane. Understanding these gap acceptance decisions can help mitigate the risks associated with overtaking. Previous research on overtaking has focused on the factors influencing gap acceptance decisions. However, the cognitive processes underlying gap acceptance decisions remain poorly understood. Previous studies have shown that response time (i.e. the time it takes the driver to evaluate the gap and make a decision) can provide valuable insights into the cognitive processes during gap acceptance decisions, in particular in pedestrian crossing and left turn decisions. However, the more complex nature of the overtaking maneuver renders it difficult to measure response times in overtaking. As a result, response times in overtaking have not been investigated, thereby limiting our understanding of overtaking behavior. To address this gap, in this paper we propose a method to measure response time in drivers' overtaking decisions and demonstrate this method in a driving simulator experiment ($N = 25$). Specifically, we analyzed the effect of distance to the oncoming vehicle and speed of the ego vehicle on response time in accepted and rejected gaps. We found that response times for rejected gaps were on average longer than for accepted gaps. The response times increased with the distance gap and decreased with the initial velocity of the ego vehicle. We conclude that using the proposed method for measuring response time can give insight in the way drivers make gap acceptance decisions during overtaking. These results provide basis for cognitive process models that can help further understand overtaking decisions.

1. Introduction

Overtaking a vehicle with oncoming traffic can be a difficult and dangerous manoeuvre. When the driver misjudges the gap to the oncoming vehicle, it could cause hazardous situations. Perception and evaluation of a gap can be classified as a gap acceptance decision and is one of the most complex processes during driving (Branzi et al., 2021). During this decision, the driver has to decide whether to accept the gap and overtake in front of an oncoming vehicle or reject the gap and wait for that vehicle to pass (Fig. 1). This requires a driver to correctly perceive and process visual information about the traffic situation and make a decision based

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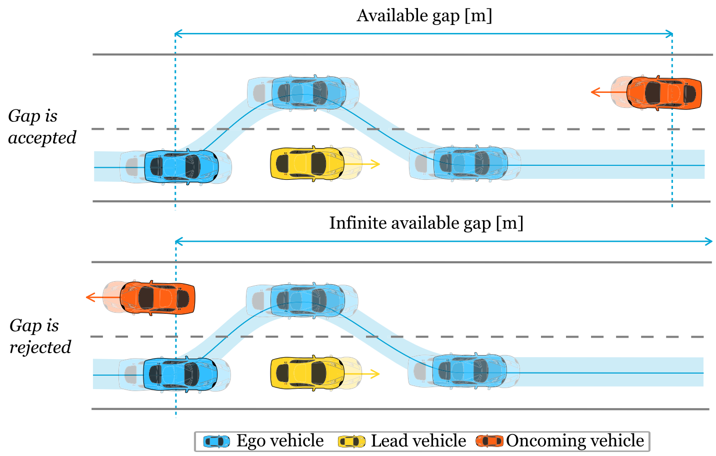

Fig. 1. Overtaking manoeuvre with traffic in the opposite lane. The top panel shows the trajectory when a gap is accepted, where the driver overtakes the lead vehicle in front of the oncoming vehicle. The bottom panel shows the trajectory when a gap is rejected, where the driver waits until the oncoming vehicle has passed to overtake the lead vehicle.

on this information. Drivers often make errors during this evaluation and decide by mistake to overtake in a hazardous situation, which is the main cause of accidents in overtaking situations (Gray & Regan, 2005, Papakostopoulos et al., 2015). Understanding gap acceptance decisions can help mitigate the risks associated with overtaking.

One approach to better understand gap acceptance decisions is to investigate what factors influence drivers' decisions. Much of existing research on overtaking is focused on investigating the effect of various factors on probability of the driver accepting the gap. In such studies, the focus lies on the *outcome* of the decision. Discrete choice models have been developed that take into account driver characteristics, geometric road characteristics and the traffic conditions (Farah & Toledo, 2010, Levulis et al., 2015, Llorca et al., 2013). In these models, the overtaking manoeuvre is divided in two steps: evaluation of intention to overtake the lead vehicle and gap acceptance. These models revolve around the notion of *critical gap*, which serves as a threshold, i.e. gaps that are larger than the critical gap are accepted (Toledo, 2007).

To model the critical gap, Farah and Toledo (2010) divided the influencing factors in situation-specific variables (such as the speed of the lead vehicle and oncoming vehicle) and latent drivers' characteristics (which are constant for each individual). The size of the available gap (a situation-specific variable, expressed in terms of distance and/or time) positively affects the gap acceptance probability (Farah & Toledo, 2010). The velocity of the ego vehicle and the oncoming vehicle together with the distance determine the time gap. The influence of the velocity of both the overtaking and oncoming vehicle separately has also been described by Ameera and Verghese (2019). With regard to the latent characteristics, Albert and Bekhor (2019) found and described the influence of personality characteristics that describe drivers' aggressiveness and risk-taking during driving. They found variations between the impact of these variables on the gap acceptance decision, emphasizing the importance of accounting for individual differences in drivers.

Complementing the studies of the determinants of the overtaking decision outcomes, Llorca et al. (2013) investigated what influence certain factors (e.g. age and gender) have on the total overtaking time, defined as the time spent on the opposite lane. They emphasize the importance of understanding the underlying mechanisms of why and how a driver makes a decision, not only what decision they make. This is also emphasized by Gray and Regan (2005), who investigated the perceptual processes during overtaking. However, both these studies still approached the gap acceptance decision as a momentary choice, and not as a prolonged, dynamic process. Thus, despite the many insights into gap acceptance behavior, the current literature lacks investigations of cognitive processes during overtaking.

Recently, cognitive models (i.e. models that computationally describe cognitive processes) have been shown to explain dynamics of gap acceptance decisions in taking a left turn at an intersection (Zgonnikov et al., 2022) and pedestrian crossing (Pekkanen et al., 2022, Markkula et al., 2022). With the help of such models, underlying processes could be unveiled, such as evidence accumulation, and the mechanisms through which different factors affect these processes can be illuminated (e.g. the role of time pressure resulting from the need to make the decision fast before the oncoming traffic is too close (Zgonnikov et al., 2022)).

An important aspect (and often a prerequisite) of cognitive process modeling is measuring the response time. In the two-choice decision-making process (in our case, either accept the gap or reject), the response time can also be described as the perception-reaction time, as it is measured from the moment the perceptual information is presented to the moment a response is executed (Durrani et al., 2021, Clithero, 2018). The response time offers insights into how a driver perceives and processes the information to come to a decision and can in itself characterize the cognitive processes underneath these decisions (Donkin & Brown, 2018). For example, long response times could indicate a difficult decision (Clithero, 2018). The response time can also provide insight into the trade-off between speed and accuracy of a decision (Brown & Heathcote, 2008).

However, despite potential benefits offered by response time measurements, existing research lacks detailed investigations of response time in overtaking decisions. The only related existing study is the one by Karimi et al. (2020) who measured "perception-reaction" times in accepted gaps, but did not analyze those. One possible reason for this lack of response time analyses in the literature is the inherent complexity of the overtaking manoeuvre: there are no apparent cues associated with the start and the end of the decision-making process. For instance, the driver can have a desire to overtake at any given time, but can wait to evaluate the gap and start the decision-making process. This complicates the measurement of the response time in overtaking, especially in rejected gaps. The fact that the decision takes place while the involved vehicles continue to move, continuously changing the situation, further complicates measurement of response times in overtaking decisions.

This paper offers a simple way of measuring response time in overtaking, and explores the effect of two situation-specific factors (distance gap and ego vehicle velocity) on the response times measured in a driving simulator experiment. The experiment therefore illustrates the use of the proposed method for measuring response time of the decision process during overtaking. Finally, we analyzed the driver's behavior during the decision process to highlight the relationship between ongoing cognitive processes and resulting vehicle dynamics.

2. Measuring response time during overtaking gap acceptance

This section describes the proposed method for measuring the response time. First, a few requirements are set for measuring the response time during overtaking. Then, the existing methods in literature for measuring the response time are discussed. After this, our novel method is explained and evaluated using the set requirements.

2.1. Response time measure requirements

We argue that in order for the response time measure to be theoretically justified and practically applicable, it has to satisfy certain requirements. First, the start time and end time of the decision process should be distinguishable for both accepted gaps *and* rejected gaps (as opposed to just one of those). Response times for both decision outcomes can provide a more complete characterization of the cognitive processes compared to just one kind of response times (e.g. only accepted gaps (Karimi et al., 2020)).

Second, ideally it should be possible to measure the response time based on basic kinematic data, without the use of additional tools such as eye trackers or brain imaging techniques. This way the measure can be applied not only to the data collected in driving simulators, but also to field data.

Finally, the response time measurement should be aligned as closely as possible with the actual process of evaluating the gap. This means that the measured start of the decision process should ideally coincide with the moment the driver starts evaluating the gap, and the measured end of the decision process marks the moment when the driver makes the decision.

In addition to these requirements, the rest of this paper will assume that the vehicles are driving on the right side of the road, and that the driver of the ego vehicle already has intention to overtake the lead vehicle.

2.2. Existing methods for measuring response time

The only existing study that reported measurements of response time is that by Karimi et al. (2020). They defined the perception-reaction time using the relative position of the driver in the overtaking situation. They used a platoon of vehicles driving in front of the oncoming vehicle. The start of the decision time was defined as the moment the last vehicle of the platoon passed the participant. A downside to this, is that this method can only be applied when other traffic (such as the platoon) is present in the opposite lane during the overtaking situation. The end of the decision time was defined as the moment the manoeuvre started, when the participant would cross the lane divider to the left lane. The rejected gaps were neglected, because they did not define an appropriate end of the decision process. This can be explained by the objective of the research, which was to compare the properties of overtaking behavior (e.g., duration of the overtaking manoeuvre, perception-reaction time) in a field experiment and a driving simulator experiment for two participant groups. At the same time, these variables, including the response time, were not analyzed beyond this comparison. So, the measurement of response time only needed to be consistent between these two study environments and groups, but was not aimed at analyzing the decision process itself.

2.3. Novel method for measuring the response time

The method proposed here (Fig. 2) builds upon the method proposed by Karimi et al. (2020) and extends it in two ways. First, both accepted *and* rejected decisions can be determined. Second, the start of the decision is based on the information actually perceived by the driver of the ego vehicle.

We divide the process of calculating the response time into three steps. First, a decision outcome must be determined after the manoeuvre is executed. Second, the start of the decision is defined. Finally, the end of the decision is determined depending on decision outcome, which together with the start of the decision defines the response time.

Decision outcome The decision outcome is determined simply based on whether the driver overtook the lead vehicle in front of or behind the oncoming vehicle (Fig. 1).

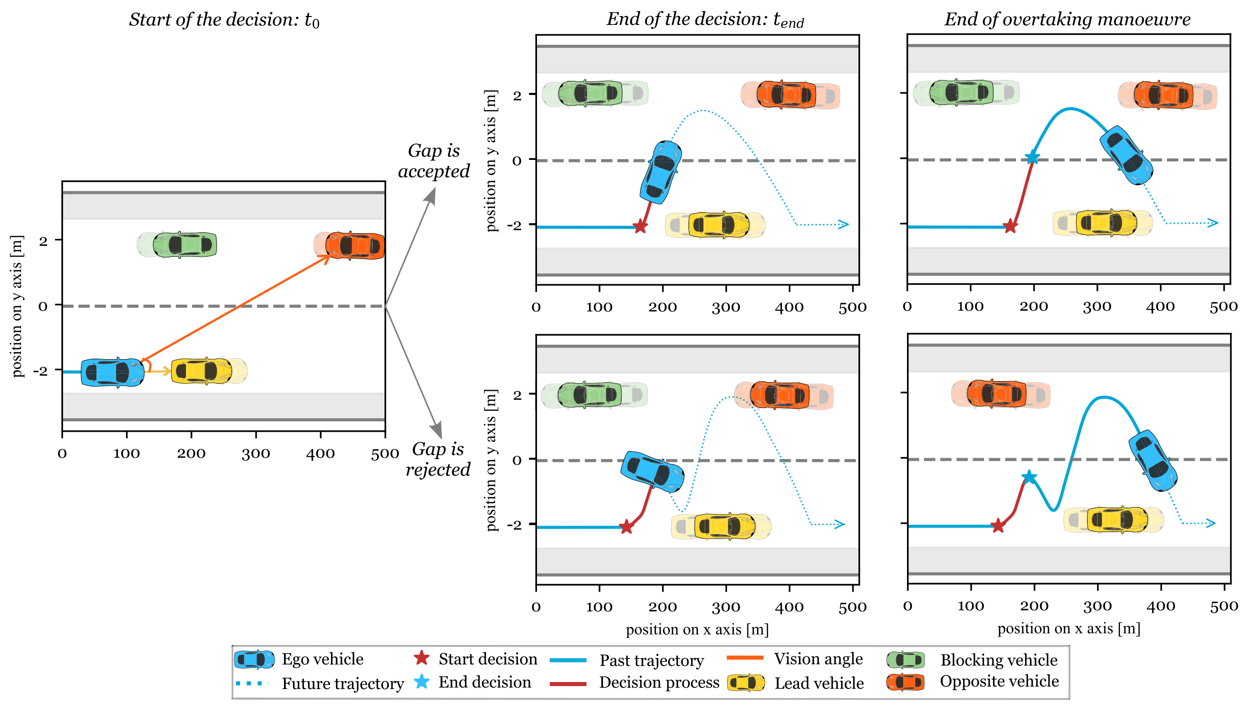

Fig. 2. Schematic overview of the definition of the start and end of the response time and the end of the overtaking manoeuvre for both accepted gap decisions and rejected gap decisions, as used in the proposed measurement method. The surrounding traffic is shown at their positions at the start and end of the decision process.

Start of the decision-making process (t_0) Gap acceptance decisions start when the perceptual information relevant to the decision is first presented (Durrani et al., 2021, Clithero, 2018). Based on this, the start of the gap acceptance decision process is defined as the moment the driver *can first see the oncoming vehicle*. In our method, this moment is determined by finding the moment when the lead vehicle does not break the ego vehicle driver's line of sight to the oncoming vehicle anymore. This is done by comparing the angles between the driver position in the ego vehicle to the left back of the lead vehicle and to the right front of the oncoming vehicle (Fig. 2). Once the angle between the ego vehicle and oncoming vehicle is the largest of the two, the view is no longer blocked by the lead vehicle. The driver can see the oncoming vehicle and the decision-making process starts.

End of the decision-making process (t_{end}) Our method assumes that in order to be able to see the oncoming vehicle, the driver has to slightly shift the lateral position of the ego vehicle to the left of their original lateral position. If the gap is then *accepted*, the driver can continue steering to the left and overtake the lead vehicle. In this case, we consider the decision process to end when the overtaking manoeuvre starts, which is marked by the ego vehicle crossing the lane divider (similar to (Karimi et al., 2021)). However, if the gap is *rejected*, the driver has to return to their original lateral lane position, which would then result in the overall trajectory of the ego vehicle swerving back to wait for the oncoming vehicle to pass (Fig. 2). Therefore, when the gap is *rejected*, we consider the decision process to end at the peak of the swerve.

To summarize, this method can be applied to the decision process during overtaking, for both accepted and rejected gap decisions. The end of the decision process is adjusted to the decision outcome retrospectively. With only the use of the location of the ego vehicle and the lead and oncoming vehicle, the outcome, start and end of the decision can be calculated. Lastly, the resulting response times covers the whole duration of the gap acceptance decision, due to relying on the line of sight for the start of the decision and conservative estimates of the time of the end of the decision.

3. Experiment: methods

This experiment aimed to demonstrate the utility of the above response time measurement method by analyzing the influence of distance and drivers' velocity on the gap acceptance decision and response time. The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology.

3.1. Participants

Twenty five drivers (15 male, 10 female) with a valid driving license, participated in the experiment. The age of the participants ranged between 19 and 58 years old (mean 25.8, standard deviation 6.8).

Fig. 3. Participants' view of the task in the driving simulator, including the lead vehicle and the oncoming vehicle.

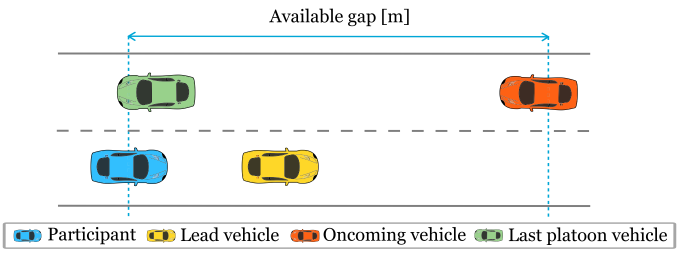

Fig. 4. The gap is defined as the longitudinal distance between the ego vehicle and the oncoming vehicle. The gap condition (160 m or 220 m) defined the size of the gap at the moment the last platoon vehicle passed the ego vehicle.

3.2. Apparatus

The experiment was conducted in a fixed-base driving simulator at the Cognitive Robotics Department, Delft University of Technology. The simulator consists of a SensoDrive steering wheel and a 65 inch screen. JOAN (Beckers et al., 2023), which builds on CARLA (Dosovitskiy et al., 2017), was used as software for the simulator. The road layout was built in RoadRunner. The data included positions, velocities, and orientation of all vehicles on the road, and was recorded at 100 Hz. Fig. 3 shows the participants' view during the experiment.

3.3. Experimental design

Each participant completed 28 short routes; in each route participants would encounter three trials (overtaking situations), resulting in 84 overtaking decisions per participant. Participants were instructed to drive through each route, overtaking the lead vehicle when they thought it was possible. The participants were also asked to not exceed a speed limit of 80 km/h throughout the experiment.

In each trial, the traffic on the road included the ego vehicle, a lead vehicle, a platoon of six vehicles and an oncoming vehicle driving behind the platoon. The experiment road consisted of three straight sections of road, connected with intersections (Fig. 5). Participants were instructed to turn right at the intersections. This way the intersections were used to divide the three overtaking situations, each situation took place at a separate section of road (Fig. 5).

The lead vehicle drove at a low constant speed of 30 km/h to induce a desire to overtake in the participants (Stefansson et al., 2020, Bar-Gera & Shinar, 2005). Furthermore, the lead vehicle drove 0.2 m left from the lane center towards the opposite lane. This way, the view of the participant on the oncoming lane was partially blocked so they had to swerve towards the opposite lane to fully see the oncoming vehicle and available gap. This was implemented to satisfy the assumption of the last step of the response time measurement method. All vehicles in the platoon had a constant velocity of 45 km/h. The platoon blocked the opposing lane, making it impossible to overtake the lead vehicle. This way, the start of the overtaking situation could be controlled.

The oncoming vehicle (Fig. 4) appeared at either 160 m or 220 m (chosen randomly at each trial) from the ego vehicle when the last platoon vehicle passed the ego vehicle. The speed of the oncoming vehicle was 0 for the first 1.2 s after it appeared on the track, and then increased steadily with acceleration of approx. 4 m/s^2. The participants could decide whether they wanted to wait until the oncoming vehicle had passed them or to overtake in front of the oncoming vehicle.

3.4. Measures

For each trial, we calculated three metrics: the decision outcome, response time, and the net velocity change of the ego vehicle during the decision process. First, we determined whether the participant executed an overtaking manoeuvre at all. If they did

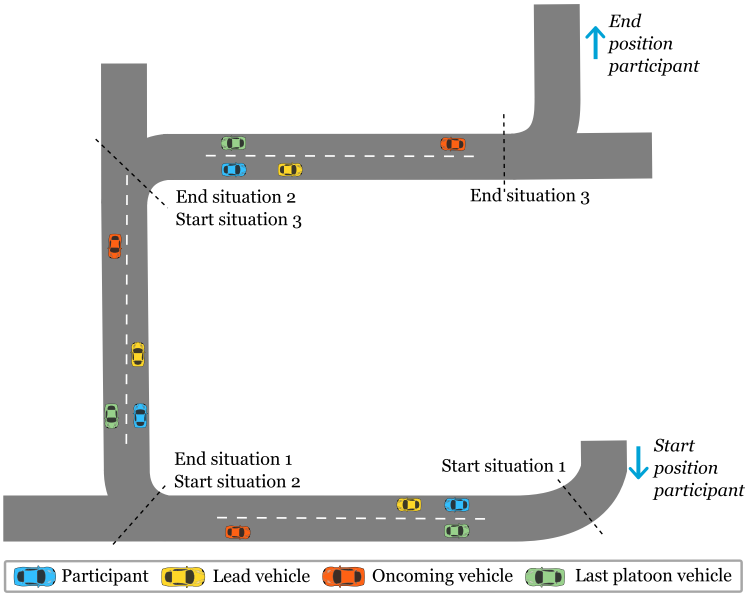

Fig. 5. Experiment design: each trial consists of three overtaking situations. For simplicity, only the last platoon vehicle is shown.

execute an overtaking manoeuvre, it was determined whether they overtook the lead vehicle before or after the oncoming vehicle. If they overtook before the oncoming vehicle the decision was marked as ‘accepted’ and if they waited until the oncoming vehicle had passed them the decision was marked as ‘rejected’. The response time was then calculated according to the method introduced above, depending on the decision outcome. However, in 6% of the decisions, the participant did not show the swerving behavior that was required to calculate the response time of rejected gap decisions. These trials, mostly contributed by one participant, could not be analyzed. As these trials represented 25% of all decisions of that participant, we excluded this participant from further analyses. Finally, we calculated the net change of the ego vehicle velocity during the decision process by subtracting the velocity at the start of the decision from the velocity at the end of the decision.

3.5. Statistical analysis

Mixed-effects models were used for statistical analysis. For the model with decision as the dependent variable, a logistic model was used, with “accepted gap” decision coded as 1 and “rejected gap” decision as 0. The distance gap and the participants’ velocity were used as independent variables.

Linear models were used for the response time and the velocity change. The decision outcome, distance gap and the participants’ velocity at the start of the decision were included in the response time model. For the velocity change model only the decision outcome and distance gap were used as independent variables.

In each model, the participant number was included as a random effect and individual intercepts were calculated for each participant. The slopes of the models were fixed between the participants. Before estimating the parameters of the model, the variables (except the decision variable) were z-scored. This way, the coefficients β for each independent variable represent their relative contribution to the dependent variable. To find the actual contribution of each independent variable, β coefficients were transformed to unstandardized coefficients b.

All statistical analyses were performed using the `pymer4` package in Python (Jolly, 2018).

4. Experiment: results

4.1. Representative behavior

The behavior of a representative participant (Fig. 6) illustrates the importance of vehicle trajectories for determining the decision outcome and the response time. First, a clear difference could be seen between the trajectories corresponding to accepted and rejected gaps (Fig. 6, leftmost panels). Specifically, in the case of rejected gaps, the participant demonstrated the expected peeking/swerving behavior that is required to calculate the response time for the rejected gaps. Second, at the start of the decision process (t_0), the participant was already moving towards the left lane. These two observations confirmed the assumption that the participant had to swerve to the left in order to properly see the available gap.

Even though certain differences in velocity between accepted and rejected gaps could be observed already at t_0, these changes increased fast over the duration of decision (Fig. 6, second-left panels). In accepted gaps, the participant started to accelerate at the start of the decision process and maintained a steady acceleration during the decision process. However, When the gap was rejected,

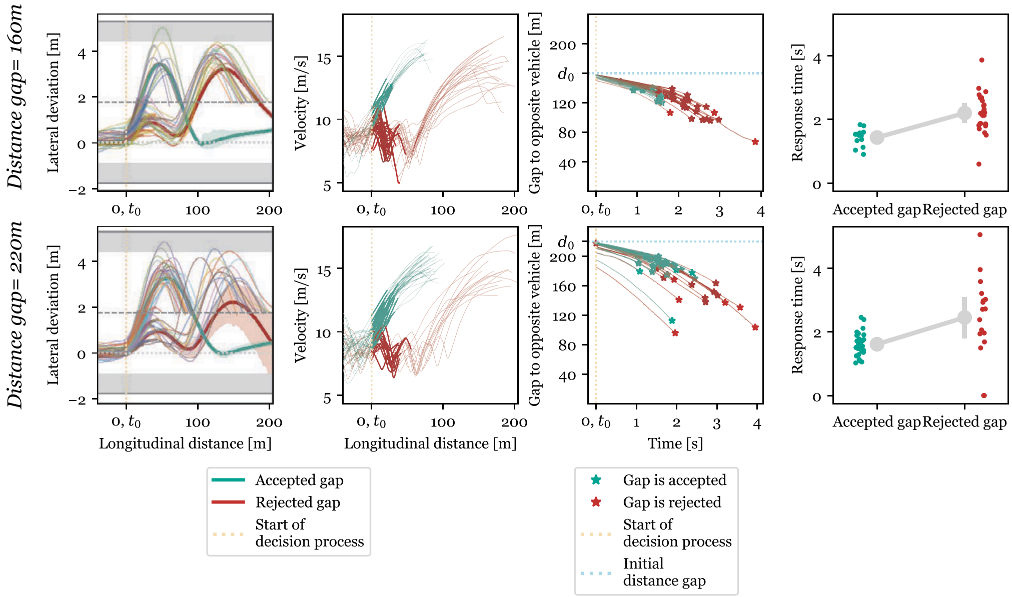

Fig. 6. Overview of the behavior of a representative participant during the decision-making process and the resulting response times for the 160 m distance conditions (top row) and the 220 m distance condition (bottom row). The leftmost panels show the changes in lateral deviation over distance (aligned at the moment of the start of the decision). The thin colored lines represent individual trials of a single participant; thick green and red lines are average trajectories across all trials of all participants. The second-left panels show the dynamics of velocity changes. The bold sections of the lines represent the duration of the decision-making process. In the third-left plots, the changes of the distance gap during the decision-making process are shown. The stars indicate the end of the decision. The rightmost panels show the response times for the accepted and rejected gap decisions. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

a more varying velocity profile was observed. The participants decreased their velocity during the “peeking” and accelerated when returning to their original position at the lane center.

During the decision process the ego vehicle and the surrounding vehicles continued to drive. Therefore, the available gap decreased during the decision process (Fig. 6, third-left panels), which the participant had to take into account when they evaluate the gap.

Finally, the response times measured in the participant were longer in rejected gaps compared to accepted gaps (Fig. 6, rightmost panels).

4.2. Decision outcome

Across all participants, the percentage of accepted gaps was higher in the large gap condition (220 m) than in the small gap condition (160 m), with $b = 0.048$, $z = 14.5$ and $p = 1.41\text{e}{-47}$ (Table 1, Fig. 7). The probability of accepting the gap also depended on the velocity of the ego vehicle: if the participant was driving faster at the start of the decision, the probability that the participant accepted the gap increased significantly ($b = 0.84$, $z = 6.48$, $p = 9.51\text{e}{-11}$).

4.3. Response time

The response time in accepted gaps was significantly lower than when the gap was rejected, with an average difference of 0.7 s ($b = -0.66$, $t = -13.4$, $p = 4.86\text{e}{-39}$) (Table 1, Fig. 8). The gap size positively influenced the response time ($b = 0.0042$, $t = 6.98$, $p = 4.03\text{e}{-12}$): when the distance gap was larger, the response time increased by 42 ms per 10 m. The ego vehicle velocity at t_0 had a negative effect on the response time ($b = -0.092$, $t = -5.76$, $p = 1.03\text{e}{-8}$): when the participants drove faster, their response time decreased with −92 ms per 1 m/s.

4.4. Velocity change

As can be seen in the response time results, the participants can spend up to several seconds deliberating on the available gap. To investigate their behavior during the decision-making process, we analyzed the difference in velocity between the start and end of the decision process. We found a significant difference in the net velocity changes between accepted and rejected gaps ($b = 4.02$, $t = 50.0$, $p < 1\text{e}{-64}$, Table 1, Fig. 9). When the gap was accepted, the net change in velocity was positive, meaning that the participants accelerated already during the decision process. When the decision process led to a rejected gap, the participants accelerated significantly less. The distance gap had a comparatively minor influence on the change in velocity ($b = 0.0062$, $t = 6.12$, $p = 1.6\text{e}{-9}$).

Table 1
Results of statistical analysis: logistic (*decision*) and linear (*response time*, *velocity change*) mixed-effects models with participant number as a random effect.

	Variable	β	b	SE	z value	p value	95% CI
Decision	Intercept	-0.0273	-17.478	0.576	-0.0474	0.962	[-1.156, 1.102]
	Distance	1.425	0.0475	0.0983	14.49	1.406e−47 (∗∗∗)	[1.232, 1.618]
	Velocity	1.309	0.8373	0.202	6.475	9.507e−11 (∗∗∗)	[0.913, 1.706]
	Variable	β	b	SE	t value	p value	95% CI
Response time	Intercept	0.949e−03	2.456	0.0696	0.0136	0.989	[-0.136, 0.137]
	Distance	0.124	0.00424	0.0178	6.984	4.033e−12 (∗∗∗)	[0.0894, 0.159]
	Velocity	-0.138	-0.0918	0.0239	-5.755	1.0253e−08 (∗∗∗)	[-0.184, -0.0907]
	Decision	-0.323	-0.662	0.0241	-13.409	4.856e−39 (∗∗∗)	[-0.3701, -0.276]
Velocity change	Intercept	-0.860	-2.251	0.0730	-11.791	9.730e−12 (∗∗∗)	[-1.003, -0.717]
	Decision	1.782	4.019	0.0357	49.967	< 1e−64(∗∗∗)	[1.713, 1.852]
	Distance gap	0.0819	0.00616	0.0134	6.118	1.159e−09 (∗∗∗)	[0.0557, 0.108]

NOTE: β = standardized coefficient, b = unstandardized coefficient, SE = standard error, CI = confidence interval, Akaike information criterion: *Decision* = 1312.4, *Response time* = 3881.2, *Velocity change* = 2877.1.
∗: $p < 0.05$, ∗∗: $p < 0.01$, ∗∗∗: $p < 0.001$.

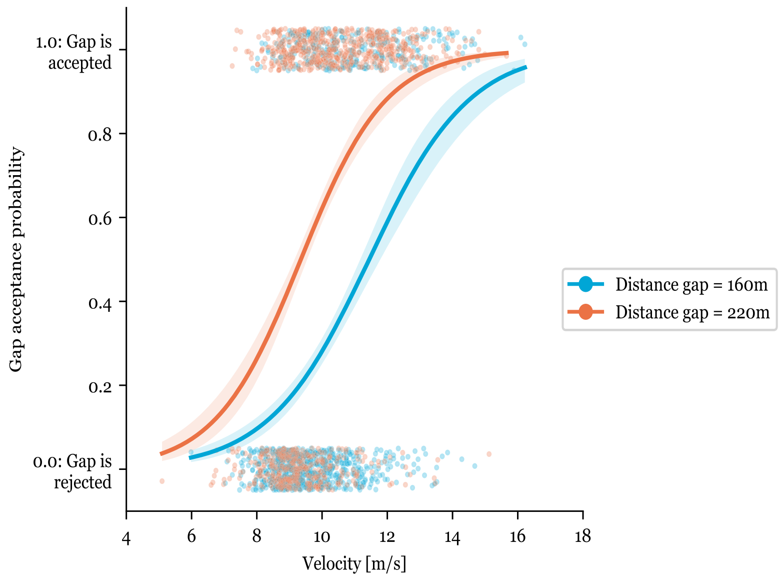

Fig. 7. Percentage of accepted gaps of all participants. The bold line represents the mean. The fitted lines do not match the mixed-effects logistic regression (Table 1), but are fitted to all participants' data for illustrative purposes using the `seaborn` package in Python (Waskom, 2021).

5. Discussion

We have developed a method to measure response times in overtaking, and analyzed the influence of the distance gap and the ego vehicle velocity on the measured response time of the gap acceptance decisions during overtaking. We found that response time was on average 0.7 s longer for rejected gaps compared to accepted gaps. Response time increased significantly with the size of the distance gap, and decreased significantly with the velocity of the ego vehicle. During the decision process leading to an accepted gap decision, the drivers increased their velocity and during the decision process leading to a rejected gap, the drivers decreased their velocity.

5.1. Method for measuring the response time

To be able to measure the response time using the proposed method, certain assumptions were made about the trajectory of the ego vehicle, depending on the decision outcome. Namely, it was assumed that the participants had to swerve towards the opposite lane to fully see and evaluate the available gap. Then, if they rejected the gap, they would return to their lane and overtake the lead vehicle after the oncoming vehicle had passed them. Their trajectory would then show a peak before the overtaking manoeuvre. When analyzing the data and applying the method to measure the response time, it was evident that the participants showed this behavior which validated the assumption, with few exceptions. The method was therefore applicable to both rejected and accepted gap decisions, such a method has been missing from the literature until now.

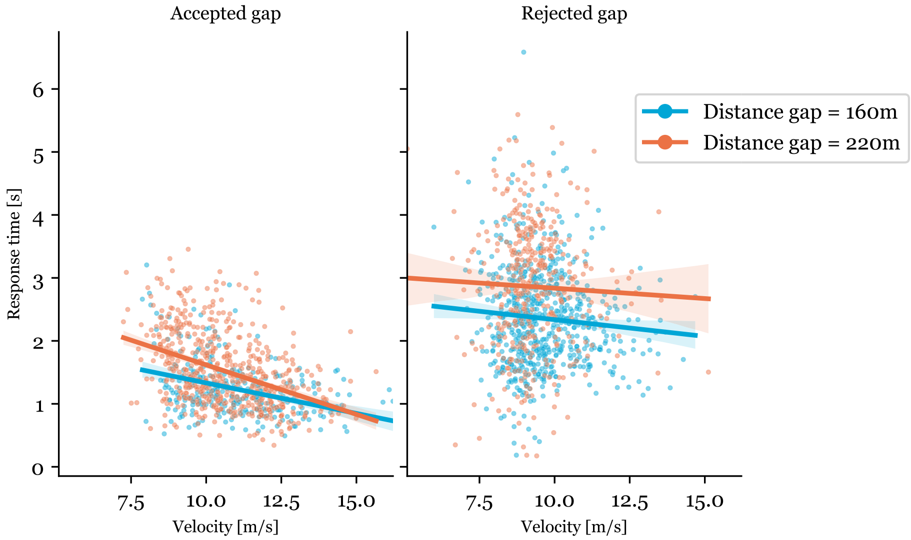

Fig. 8. Response time of accepted gaps of all participants. The bold line represents the mean. The fitted lines do not match the mixed-effects linear regression (Table 1), but are fitted to all participants' data for illustrative purposes using the `seaborn` package in Python (Waskom, 2021).

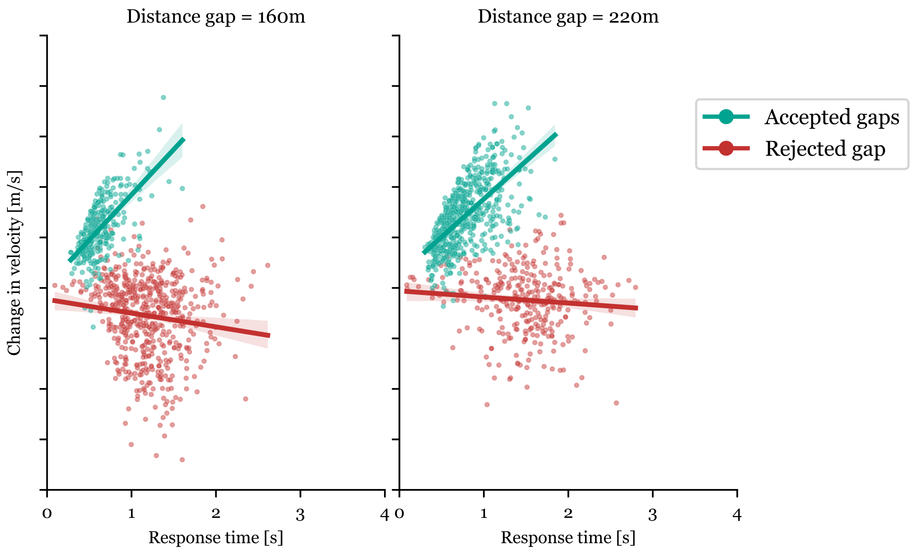

Fig. 9. Changes in the velocity of the ego vehicle during the decision process for all participants as a function of distance gap, decision outcome, and response time.

However, the assumptions of the method should be further investigated. The start of the overtaking manoeuvre, and therefore the end of the decision process for accepted gaps, is marked at the moment the center of the ego vehicle crosses the lane divider. Alternative definitions for the start of the overtaking manoeuvre exist in current literature, which can be tested in the proposed response time measurement method in this paper. For example, Gray and Regan (2005) measured the participants' standard deviation of the lateral position and defined the start of the overtaking manoeuvre (and thus the end of the decision process) when the participant deviated a distance of three times the standard deviation towards the lane divider. Such alternative definitions can be compared to the definition used in this paper, by applying these to the same data. This way the proposed response time measurement method can be further improved.

Furthermore, the method can be extended to also account for aborted gaps. In this study the decisions can only be marked as rejected or accepted. However, research has shown that rejected gaps can also be further divided in gaps that were rejected in the first place and aborted gaps (Farah, 2016). In the case of an aborted gap, the driver has initially accepted the gap but realizes that the accepted gap unsafe and therefore decides to abort the manoeuvre. Part of the rejected gaps in this paper could potentially be aborted gaps. When the manoeuvre was aborted, the driver had already started their overtaking manoeuvre, which could also explain some of the longer response times we observed in rejected gaps.

Also, the method could be further verified using field data. A benefit of the proposed method is that it is solely based on the trajectories of the involved vehicles and no intrusive methods or additional tools are needed. So, by recording trajectories in traffic, the response times of decisions in field data could potentially be measured. However, for the method for measuring response time it is assumed that the driver has a desire to overtake. This was indirectly enforced in the experiment by making the lead vehicle drive with a speed much lower than the speed limit provided to the participants (30 km/h vs 80 km/h). To apply the proposed method on field data, a prior step should be added to determine whether the driver has a desire to overtake. In order to do this, further research should be done on how to detect a desire to pass, for example by searching for and investigating visual indicators, as done by Henning (2010) for lane changes.

From the perspective of road safety, we believe our method can help investigate the cognitive underpinnings of unsafe overtaking decisions. Previous research has distinguished between intentional (safety violations) and unintentional (errors) unsafe overtaking decisions (Atombo et al., 2016). We believe that our method, focusing on the decision process immediately preceding the occurrence of the potentially unsafe situation, can help provide insight into both safety violations and errors while overtaking.

Our approach is only the first step towards incorporating response times in research on dynamic gap acceptance decisions in traffic, and therefore has multiple limitations to be addressed in future work. First, it is likely to be limited to accelerating overtaking maneuvers (where the driver closely approaches the lead vehicle in their lane before overtaking it) and might not extend to "flying" overtaking, in which the drivers initiate overtaking early on and do not decrease their speed before starting the maneuver (Dozza et al., 2016, Farah et al., 2019). Second, an implicit assumption of our method is that the driver becomes aware of the oncoming vehicle at the very moment it appears in their field of view. We believe this is justified in the context of our experiment, but can be an important limitation in extending our method towards naturalistic data. Specifically, in real-life overtaking, the driver needs to check whether they are themselves being overtaken by another car before initiating the maneuver. This implies that during the time the driver spends on looking at the side mirror and behind their shoulder they do not attend to the oncoming vehicle, violating the assumption of our method. Whether such behavior has implications for response times remains to be tested in future work, e.g. using eye-tracking.

5.2. Experimental results

Most previous studies of gap acceptance during overtaking analyzed the influence of various factors on the probability a gap is accepted. Our findings concerning decision outcome are consistent with the previous research demonstrating positive effect of distance gap (Farah et al., 2009, Farah & Toledo, 2010) and ego vehicle velocity (Ameera & Verghese, 2019) on the probability that a gap is accepted. What our study contributes to this research is analyzing the outcome together with the process of decision making, through measuring the response time.

We found that response time in accepted gaps was lower than in rejected gaps. We envision two potential explanations for this observation. First, lower response times when accepting the gap can indicate that a driver is biased towards accepting the gap in the first place. In our experiment, by the time the driver evaluated the gap they needed to wait for that gap behind the slow lead vehicle until the platoon of six vehicles has passed. This could have made accepting the gap a *cognitive default* for the participants, resulting in shorter response times (an effect previously observed, e.g. in psycholinguistics (Meyer et al., 2011)). Second, the difference between response times in accepted and rejected gaps could be simply due to different criteria for determining the end of the decision process for the two decision outcomes. It is entirely possible that crossing the lane divider (the criterion for the end of accept gap decisions) happens on average earlier than the decision is made, potentially resulting in a systematic underestimation of response times in accepted gaps. Similarly, marking the end of the reject gap decisions at the peak of the swerving maneuver could potentially overestimate response time in the reject gap decisions, in case the decision to reject the gap is actually made before the driver steers back to their own lane. Measuring response times with a more invasive method, e.g. asking the driver to press a button to indicate the end of the decision, can further shed light on the difference between response times in accepted and rejected gaps. However, such measurements should also be interpreted with caution due to decreased ecologically validity compared to our method.

The key finding of our experiment is that response time increased with distance gap and decreased with ego vehicle speed. In cognitive psychology, longer response times are often associated with decisions requiring more complex cognitive processing (Luce, 1986). In the context of our task, this could imply that it was easier for the participants to estimate the distance to the oncoming vehicle when that vehicle was closer, thereby leading to faster decisions in the 160 m condition. This however would not explain that response time decreased with the ego vehicle speed. One potential explanation for that could be an increase in perceived urgency of the situation at higher speeds: the faster the ego vehicle is at the time the decision starts, the less time budget the driver has to make a decision before the gap closes (a similar effect has been observed previously in left-turn gap acceptance (Zgonnikov et al., 2022)). The extent to which the observed response times are driven by these two effects (response urgency and cognitive complexity) and possible other factors could be clarified in future work. Further insights into response times could also be provided by more comprehensive studies systematically manipulating not only the distance, but also the time-to-arrival of the oncoming vehicle, its size and type, as well as demographic characteristics of the drivers; all of these have been previously shown to affect the decision outcomes in overtaking (Farah et al., 2019, Levulis et al., 2015, Farah, 2011) and can therefore be important determinants of response times.

In this study, we went beyond studying the outcomes and timing of overtaking decisions, and investigated the course of the ego vehicle dynamics during the decision process. When analyzing the change of the velocity during the decision process, we found that participants started accelerating or decelerating already during the decision process, leading to accepted or rejected gaps respectively. This effect may have resulted from an interplay of two mechanisms. First, the likelihood of accepting the gap could by dynamically affected not just by the speed of the ego vehicle at the start of the decision (Fig. 8) but also by involuntary fluctuations in the speed during the process. Second, the participants could have already started adapting their speed to their tentatively preferred decision. For instance, if during the decision process the driver inclines to accept the gap, they can (deliberately or subconsciously) accelerate before the decision has even been finalized. Such explanation would be consistent with the notion that the decision-making process is not separated into consecutive steps of perception, cognition, and action, but instead the current state of the decision-making process continuously "leaks" into motor behavior throughout that process (Spivey, 2008). Such leakage has been previously observed in mouse cursor (Spivey et al., 2005), hand reaching (Song & Nakayama, 2009), and walking (Zgonnikov et al., 2019) trajectories for simpler decision-making tasks; to the best of our knowledge, this work is the first to have demonstrated signatures of such behavior in driving tasks.

Our results illustrate how response time is capable of capturing multiple aspects of complex decision making during overtaking gap acceptance. However, as the above discussion highlights, several alternative explanations may underlie our findings. Empirical research like ours is limited when it comes to disentangling candidate cognitive mechanisms for the observed timing of decisions. Future work focusing on computational cognitive modeling could help to clarify which of the above considerations provide a plausible explanation for our findings. One class of models that have provided insights into numerous response time findings before is evidence accumulation models (Gold et al., 2007, Ratcliff et al., 2016). These models have been recently adopted to model decisions in traffic, including pedestrian crossing (Pekkanen et al., 2022, Markkula et al., 2022) and unsignalized left turns (Zgonnikov et al., 2022), but never to decisions as dynamic and complex as overtaking. We believe that developing models describing evidence accumulation in overtaking gap acceptance decisions is an important avenue for future research. Such research can help to unveil the computational mechanisms underlying our empirical findings, as well as enable real-time prediction of gap acceptance behavior in automated driving systems (Schumann et al., 2023).

5.3. Conclusion

This study shows the promise of including response times in research on tactical decision making in traffic. Our results can be used in future research to link decision outcomes and response times in overtaking using cognitive process models. We believe that this will help to understand errors that drivers make while overtaking, and thereby improve road user safety.

CRediT authorship contribution statement

Annemartijne Sevenster: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. **Haneen Farah:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. **David Abbink:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. **Arkady Zgonnikov:** Conceptualization, Data curation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Data availability

The experimentation software code, data, and analysis scripts are publicly available at https://osf.io/k3cmn.

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