MSc Thesis

Analyzing the relation between the gap acceptance behavior and the response time of drivers' decisions during overtaking

Annemartijne Sevenster
4368649

Delft University of Technology

TU Delft

Department of Cognitive Robotics

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Annemartijne Sevenster

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Thesis committee:	Prof. dr. ir. D. A. Abbink,	TU Delft, supervisor
	Dr. ir. H. Farah,	TU Delft, supervisor
	Dr. A. Zgonnikov,	TU Delft, supervisor
	Dr. E. Papadimitriou,	TU Delft, external member

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Preface

Dear reader, I am proud to introduce to you my final master's thesis. If you had told me 7 years ago that I would do my graduation thesis in Vehicle Engineering I probably would not have believed it. I would have laughed if you would have told me that I was going to develop a method to measure drivers' response time and conduct a driving simulator experiment with 25 participants. However, I am happy and proud to say that I managed to do it and that I enjoyed it. I really have found my passion for human factors.

I have had my ups and downs this past year and I could have never presented this final thesis without a lot of people. I would like to thank my supervisors, Arkady, Haneen and David. Arkady, thank you for introducing me to the topic of gap acceptance and response times. You really pushed me to deliver the best work possible and helped me face the struggles of doing research . I wonder if there is ever going to be a day that I won't pay attention to my own response times and gap acceptance decisions. Haneen, thank you for helping me understand how overtaking works and for teaching me that taking a day off is sometimes better than to keep working. I have used your advice for my friends who are also graduating and it has helped them a lot too. Last but certainly not least, I want to thank David, for enthusing me about human driving behaviour and for your creative ideas that brought my research to a higher level. I always felt better and full of motivation after our meetings. Most importantly, thank your for teaching me to always, *always* do a pilot study. Special thanks to Niek, Olger and Timo for your help throughout the process. You were not my supervisors but you were always ready to lend me a helping hand. I'd like to thank my participants, without whom I really could have never presented this work.

Then, there are a few people that deserve a shoutout for keeping me company at the TU this year. Merijn, Dirk and Maurits, this year would have been insufferable without our fun breaks and car rides to Delft. Valerie, Maura, Leo and Toet, it always helped a lot to talk to you about our thesis frustrations. Wouter and Lorenzo, I really liked our days at the Haptics Lab helping each other with our experiments and again, thanks for never complaining about my noisy computer. Willie and Mattie, thank you for reading my paper and giving me the most comments I have ever seen. My roommates, you gave me distraction and good food whenever I needed it.

Then, most importanly, I want to thank my parents and my sister. Mam, thank you for the encouraging messages every single day and for coming all the way from London to be my first participant. Pap, thank you for your good advice, especially your motto, ”you cannot do any better than your best”. Fré, thank you for your concern and support, it never went unnoticed. I'm sorry to all of you for ignoring your texts this year and always using my thesis as an excuse.

Annemartijne Sevenster
Delft, January 2022

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1

Paper

Analyzing the relation between the gap acceptance behavior and the response time of drivers' decisions during overtaking

Annemartijne Sevenster

***Abstract*—Overtaking on two-lane roads can cause dangerous situations, due to drivers' errors during the gap acceptance decision. Understanding gap acceptance decisions can help mitigate these situations. Response time (i.e. the time it takes the driver to evaluate the gap and make a decision) has been shown to provide valuable insights into the cognitive processes during gap acceptance decisions in pedestrian crossing and left turn decisions. However, for overtaking, previous studies have not investigated the response time. I investigated how factors that play a role in gap acceptance decisions during overtaking (namely, size of the gap and the drivers' velocity) influence the response time. I also studied the change of the drivers' velocity during the decision process. I proposed a novel method to measure the response time in drivers' overtaking decisions, and conducted an experiment to demonstrate the usefulness of the method. 25 participants were presented with multiple overtaking situations in a driving simulator experiment, with varying distance gaps. I analyzed how the probability of gap acceptance varied with the distance gap and participants' velocity at the start of the overtaking situation using a generalized logistic mixed model. I also analyzed how the response time varied with the distance gap, participants' velocity and the decision outcome using a linear mixed model. Lastly, I analyzed if the velocity changed between the start and the end of the decision process and whether there was a relation between the decision outcome and the distance gap and the velocity change, using a linear mixed model. The probability of accepting a gap increased significantly with the distance gap and the velocity of the participant. The response times for rejected gaps were on average 0.7s longer than accepted gaps. The response time increased with the distance gap (42ms per 10m), but decreased with the velocity (-92ms per 1m/s). The velocity changed differently between the decision processes leading to either decisions, with an average difference of 4 m/s. Using the proposed method, I found that the factors which influence the outcome of the decision, also influence the response time. The dependence of response time on the distance gap and participants' velocity could be explained by the speed-accuracy tradeoff or the difficulty of the decision. Furthermore, it was shown that the drivers already adapt their velocity during the decision process, instead of after they have made their decision. So, I can conclude that using the proposed method for measuring response time can give insight in the way drivers make gap acceptance decisions during overtaking. My results provide basis for cognitive process models that can help further understand the results and are capable of predicting decision outcomes and response times.**

1. Introduction

Overtaking a vehicle with oncoming traffic can be a difficult and dangerous manoeuvre. When the driver misjudges the gap with 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 [1]. During this the decision the driver essentially has to decide to accept the gap and overtake in front of an oncoming vehicle (see Figure 1). It requires a driver to correctly perceive and process visual information about the traffic situation and make a decision based on this information. It has been found that 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 [2, 3]. Research has been done to improve the understanding of gap acceptance decisions during overtaking, in order to understand why these errors occur.

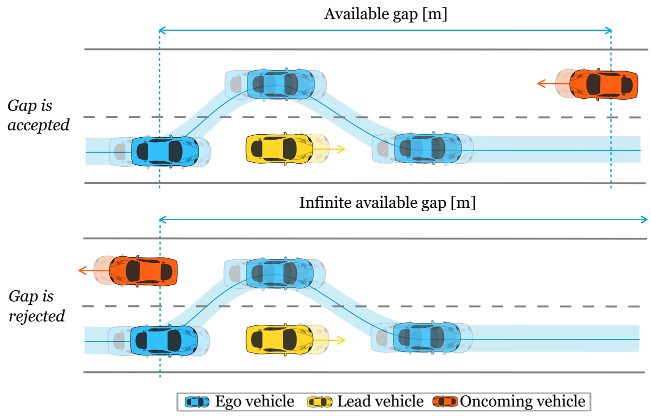

Fig. 1: An overtaking manoeuvre with traffic in the opposite lane. The upper plot shows the trajectory for when a gap is accepted, where the driver overtakes the lead vehicle in front of the oncoming vehicle. The bottom plot shows the trajectory when a gap is rejected, where the driver waited until the oncoming vehicle has passed them to overtake the lead vehicle.

One approach to better understand gap acceptance decisions, is to investigate what factors influence drivers' decisions. Most previous research is focused on calculating the probability a gap is accepted, dependent on these factors. In such studies, the focus lies on the *outcome* of the decision. Discrete-choice models, for example, have been developed that take into account driver characteristics, geometric road characteristics and the traffic conditions [4–6]. In these models the overtaking manoeuvre is divided in two steps: the decision whether there is a desire to overtake and the decision to accept a gap and overtake or reject the gap. These models use a *critical gap*, which serves as a threshold, i.e. gaps that are larger than the critical gap are accepted [7].

To model the critical gap, Farah et al. [4] 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 as a situation-specific variables and it was shown that this gap size positively impacts the gap acceptance probability. The available gap can be expressed in distance and time, namely the distance gap and the time gap. The velocity of the overtaking driver and the oncoming vehicle together with the distance determine the time gap. The influence of the velocity of both the overtaking and oncoming vehicle seperately has also been described by Ameera et al. [8]. With regard to the latent characteristics, Albert et al. [9] 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 individualities in drivers.

Llorca et al. [6] investigated what influence certain factors (e.g. age and gender) have on the overtaking time instead of the decision outcome, 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. This is also emphasized by Gray et al. [2], after investigating the perceptual processes during overtaking. However, both approached the gap acceptance decision as a final outcome to a binary choice and not as a decision process.

The current literature on the gap acceptance decisions lacks in investigating the underlying processes during the decision-making [10, 11]. Cognitive process models, that can model the thinking process, have shown to be able to explain these processes. For example, evidence accumulation models have been applied to the gap acceptance decisions when taking a left turn at an intersection [12]. With the use of the evidence accumulation model several underlying processes could be unveiled, such as the role of time pressure of oncoming traffic on the decision process.

An important aspect of the cognitive process models is measuring the response time. In the two-choice decision-making process (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 [13, 14]. The response time offers insight in how a driver perceives and processes visual information to come to a decision and can in itself explain the cognitive processes underneath these decisions [15]. For example, if the response time increases, this could indicate a difficult decision [14]. The response time can also provide insight into the trade-off between speed or accuracy (in the case of a gap acceptance decision, a safe gap) [16]. It gives an indication on the personal driving behavior - does the driver prioritize a quick decision over a safe decision?

To summarize, it has been shown that together with decision outcome data and evidence accumulation models, the response time is capable of predicting decision processes [12, 14].

The response time measurement also creates a possibility to analyze the behavior of a driver during the decision process. In response time research it is assumed that the decision process ends once the driver execute an action (for example accelerate, brake or start the overtake manoeuvre), so during decision process his driving behavior is constant. This is the case during gap acceptance decisions for pedestrian crossing and left-turns, where the decision-maker is standing still [12, 17]. However, decisions during overtaking differ from other gap acceptance decisions, because the driver has to continue driving while simultaneously deliberating his decision. Measuring the response time gives the opportunity to analyze the behavior during the decision process, which can give insight on how drivers behave if they have to make a decision in a dynamic situation.

However, not much research has been devoted to the response time of the decisions during overtaking. Overtaking is a complicated manoeuvre in terms of response time, because there is no visible or external cue when the decision-making process starts. 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. The fact that the decision takes place while the vehicles involved continue to drive, continuously changing the situation, further complicates the overtaking decision. As said before, there has been done a lot of research on the outcome of gap acceptance decisions of overtaking and what factors influence these decisions, but not yet what factors influence the response time. This research aims at answering the question how the influencing factors of gap acceptance decisions during overtaking influence the response time. This question can be seen as a first step in improving the understanding of the decision-making process during overtaking.

To answer this question I developed a method to measure the response time of the decision-making process during overtaking, applicable to both completed and rejected overtaking manoeuvres. The proposed method is used in a driving simulator experiment, in which the influence of distance gap and drivers' velocity on the gap acceptance decision and response time was measured. In previous research these factors have been shown to have an influence on the gap acceptance decision [4]. When studying the influence on the response time, the relation between the gap acceptance decision and the response time was analyzed and

measured. The experiment therefore illustrates the usability of the proposed method for measuring response time of the decision process during overtaking.
Furthermore, after the response time is calculated, I analyzed the driving behavior during the decision process will, by calculating the velocity difference between the start and end of the decision process.

I hypothesized that,

- the size of the distance gap influences the drivers' decision and response time;
- the drivers' velocity at the start of the overtaking situation also influences the drivers' decision and response time;
- during the decision process the drivers' velocity stays constant and changes after the decision has been made.

First, the method for measuring the response time will be explained. After this, the experiment will be described. Then, the results will be presented and used to illustrate the use of the response time method. Lastly, the results will be discussed and followed by a conclusion.

2. Measuring response time during overtaking

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, the novel method is explained and evaluated using the set requirements.
As described before, the response time of the decision process during overtaking is difficult to measure. This is due to the lack of an external cue when the driver feels a desire to overtake and starts to evaluate the traffic situation. Therefore, in current literature overtaking behavior is usually analyzed from the start of the manoeuvre, which is a visible cue. A common definition of the start of the manoeuvre is when the driver crosses the lane divider towards the opposite lane.

2.1 Response time method requirements

In order to analyze the response time of the decision-making process a few requirements are set. Firstly, a start time and end time of the decision process should be distinguished, for both accepted gaps and rejected gaps. Research has been done on the distinction between rejected and aborted overtaking manoeuvres [18], however this research only focuses on rejected gaps. Insight into the response time of both decisions can improve the knowledge of how and why a driver accepts or rejects a gap, instead of only evaluating why a driver accepts a gap. Furthermore, it should be possible to measure the response time during experiments, without the use of additional tools such as eye trackers or brain imaging techniques. This way the method can be applied to field data in future research. Thirdly, as explained before, the gap acceptance decision is based on visual information, so the decision process should be based on the perception of this visual information. In comparison, when looking at response time measurements for other perceptual decisions during driving, the start of the decision is defined as when the driver is first presented with the decision.
Lastly, it is important that the response time only addresses the cognitive decision process regarding the gap acceptance decision and no other decision processes that occur during driving. For example, while a driver is evaluating the gap he also has to maintain a safe distance to the lead vehicle, requiring certain car-following decisions regarding the following distance. The proposed method to measure the response time should only capture the relevant processes. As shown in Figure 1, a gap acceptance situation consists of the ego vehicle, a lead vehicle and an oncoming vehicle. The gap acceptance decision regards a driver who desires to overtake a lead vehicle and the gap between the overtaking driver and the oncoming vehicle and the response time measurement should therefore only concern these vehicles.

2.2 Existing methods for measuring response time

Karimi et al. [19] defined the perception-reaction time using the relative position of the driver in the overtaking situation. They uses 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 different variables 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. These different variables, such as the response time, were not analyzed. 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 proposed method in this paper improves the existing methods in two ways and is visualized in Figure 2. Firstly, both accepted *and* rejected decisions can be determined. Secondly, the start of the decision is based on perception. To calculate the response time the analysis is divided in three steps. First, a decision must be determined. Then, the start of the drivers' perception is defined, after which the driver reacts to this perception, which ends the response time. In order to calculate the response time with the proposed method, it is assumed that the driver has a desire to overtake.

Decision: After each trial it can be determined whether the driver has accepted or rejected the gap. If the driver overtook the lead vehicle in front of the oncoming vehicle, the driver has accepted the gap (see Figure 1). Depending

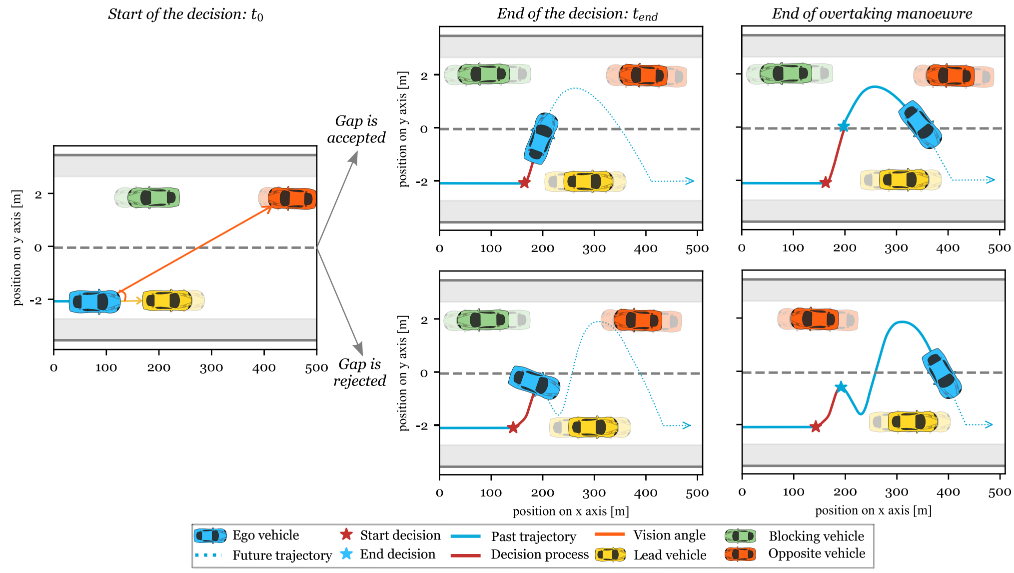

Fig. 2: Schematic overview of the definition of the start and end of the response time and the end over the overtaking manoeuvre for both accepted gap decisions and rejected gap decisions, as used in the proposed measurement method. The shaded area at the laneborders represent the location where the vehicle starts to drive off-road, to give an indication of the vehicle dimensions. The surrounding traffic is shown at their positions at the start and end of the decision process.

on the outcome of the decision the response time can be measured.

Start of the decision-making process (t_0) - Perception: Gap acceptance decisions are distinguished as perceptual decisions - the decisions are based on the processing of visual information [2]. Such decisions start when the perceptual information is first presented [13, 14]. Based on this, the start of the decision process is defined as the moment the driver *can see the oncoming vehicle*. This moment is determined by calculating 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. Once the angle between the ego vehicle and oncoming vehicle is the largest, 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}) - Reaction: Based on the final decision outcome, the end of the decision-making process can be determined. However, independently from the decision outcome the driver has a desire to overtake. To fulfill this desire the driver will evaluate the situation and decide whether there is a possibility to overtake. In order to do this, the driver has to be able to fully see the available gap. When a slow driving lead vehicle is blocking the view, the driver has to swerve to the left during the decision process. When the gap is then *accepted*, the driver can continue steering to the left and overtake the lead vehicle. The decision process ends when the overtaking manoeuvre starts, which is marked when the ego vehicle crosses the lane divider [20]. When the driver decides to reject the gap and not overtake, they have to return to their original lane. Therefore, when the gap is *rejected*, the decision process ends when the driver returns to the original lane - thus the process ends 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. Also, when calculating the start of the decision, the perception of the driver is taken into account. Lastly, the method only focuses on the decision processes regarding the gap acceptance decision. The defined start and end of the decision process are fully linked to the overtaking manoeuvre. So, the response time measurement method satisfies the necessary requirements for measuring the response time in an experiment.

3. Method

This experiment aims at analyzing the influence of distance and drivers' velocity on the gap acceptance decision and response time. The presented method for measuring the response time is applied to calculate the response time and is confirmed through this use.

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 $(M) = 25.8$, Standard Deviation $(SD) = 6.8$).

Fig. 3: The simulation environment with the lead vehicle and the oncoming vehicle.

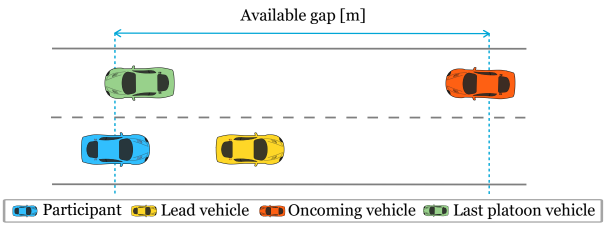

Fig. 4: The gap is defined as the longitudinal distance between the ego vehicle and the oncoming vehicle. The gap is measured at the moment the last platoon vehicle passes the ego vehicle.

3.2 Apparatus

The experiment was conducted in a fixed-base driving simulator at the Cognitive Robotics lab at the Faculty of Mechanical Engineering (3mE) at Delft University of Technology. The simulator consists of a SensoDrive steering wheel and a 65 inch screen. JOAN [21], which builds on CARLA [22], was used as software for the simulator. The road layout was built in RoadRunner. The datarecorder built in JOAN recorded at a frequency of $100Hz$. Figure 3 shows the participants' view during the experiment.

3.3 Experimental design

The experiment existed of 28 trials in which the participants would encounter three overtaking situations, as visualized in Figure 5. The overtaking situations consisted of 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. The participants were asked 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 (see Figure 5).

The lead vehicle drove at a constant speed of $30km/h$ to induce a desire to overtake in the participants [23, 24]. Furthermore, the lead vehicle drove $0.2m$ left from the lanecenter towards the opposite lane. This way, the view of the participant was slightly blocked and they had to swerve towards the opposite lane to fully see the oncoming vehicle and available gap, to satisfy the last step of the response time

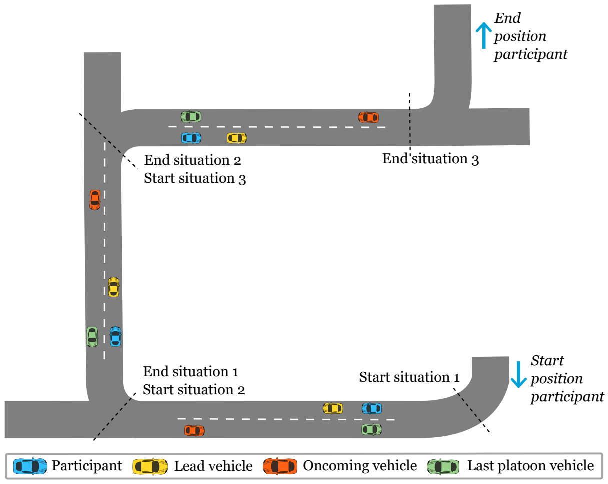

Fig. 5: Experiment design: each trial consists of three overtaking situations. For simplicity, only the last platoon vehicle is shown.

measurement method. The platoon of vehicles had a constant velocity of $45km/h$. 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 (as seen in Figure 4) appeared when the participant passed the last platoon vehicle. It was originally planned to vary the velocity of the oncoming vehicle, however the oncoming vehicle started to drive with a very low acceleration, therefore the oncoming vehicle appeared to be standing still to the participant and only the change in distance was visible. The participants could then decide whether they wanted to wait until the oncoming vehicle had passed them or to overtake in front of the oncoming vehicle. This situation was repeated on each straight road section.

In order to find the influence of distance on the gap acceptance decision and response time the gap between the ego vehicle and oncoming vehicle were varied according to two distance conditions, namely $160m$ and $220m$. The gap is defined as the distance in longitudinal direction between the ego vehicle and the oncoming vehicle, at the moment the oncoming vehicle appears, as can be seen in Figure 4. To find the influence of the drivers' velocity on the decision and response time, the velocity of the participant was measured at the same moment.

3.4 Experimental procedure

Before the experiment the participants signed an informed consent form. The participants were also given a form with instructions, which gave an explanation about the gap acceptance decision they were expected to make. The participants were asked to overtake the lead vehicle when they thought it was possible.
After this, the participants were asked to take place in the driving simulator and three training trials were performed. In

the first training trial the participant would only encounter the three lead vehicles. In the second training trial the participants would only see the three platoons of vehicles and during the last training trial all the traffic vehicles were driving in the environment. The participants were asked to not exceed a speed limit of $80km/h$ throughout the experiment.
After the experiment had started, the participant could take a 5 minute break after every 10 trials.

3.5 Dependent measures

After the experiment, three metrics were calculated with the recorded data, being the decision outcome, response time and the velocity change during the decision process.
First it was determined whether the participant executed an overtaking manoeuvre. If they did 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'.
With the use of the response time method and the decision outcome, the response time was calculated.
After the response time was calculated the change of the participants' velocity during the decision process could be calculated. This was done by determining the velocity at the start of the response time and at the end of the response time and calculating the difference.

3.6 Statistical analysis

A mixed effects model was 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 and 'rejected gap' decision as 0. The distance gap and the participants' velocity were used as independent variables.
A linear model was used for the response time and the velocity change. The decision outcome, distance gap and the participants' velocity 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 participants' individual behavior was included as a random effect and individual intercepts were calculated for each participant. The slopes or model coefficients were fixed between the participants.
Before estimating the parameters of the model, the variables (except the decision variable) were z-scored. This way, the coefficient for each independent variable represents their relative contribution to the dependent variable. To find the actual contribution of each independent variable, the z-scored coefficients were transformed to unstandardized coefficients.
The statistical analyses were performed using the `Pymer4` package in Python [25].

4. Results

In this section the results of the driving experiment will be shown.

Figure 6 gives an overview of the data of a typical participant. At the top of the two left graphs the percentage of accepted and rejected gaps is given in each condition. The ratio flips between the conditions - for the small gap condition the amount of accepted gaps is approximately $2/3$ versus $1/3$ in the large gap condition.

The trajectories of the participants are crucial to determine the decision outcome and calculate the response time. Especially in the case of rejected gaps, the drivers were assumed to demonstrate a "peeking" behavior. When analyzing the trajectories, a clear difference could be seen between the trajectories of accepted and rejected gap decisions. It was found that the participants showed the necessary behavior for calculating the response time for the rejected gaps. The two first plots on the left in Figure 6 show the difference between the lateral deviation when the participant accepted and rejected the gap. The previously described double peaks in the lateral deviation when a gap was rejected can be clearly seen. It can also be seen that the participant immediately moved towards the left lane after the defined start of the decision process (t_0). This confirms the assumption that the participant had to swerve to the left in order to properly see the available gap. However, in 6% of the decisions, the participant did not show the necessary behavior to calculate the response time of rejected gap decisions. These decisions had to be neglected. One participant contributed the largest part of these neglected decisions. 25% of his decisions had to be neglected, also due to multiple crashes, so it was decided to exclude this participant from the data analysis.

Next to the decision outcomes and the response time, the participants' velocity was analyzed during the experiment. A notable difference in velocity was seen between accepted and rejected gaps. (see Figure 6). What stands out is the difference between the velocity profiles for the accepted and rejected gap decisions. The participant starts to accelerate at the start of the decision process and maintained a steady acceleration during the decision process when they accepted the gap. When the gap was rejected a more varying velocity profile is seen. The participants decreased their velocity during the "peeking" and accelerated when returning to their original position at the lanecenter. Furthermore, when the gap was accepted the participant showed steady acceleration during the decision process. This will be further analyzed in Section 4.3.

During the decision process the participant and the surrounding vehicles continue to drive. Therefore, the available gap decreases during the decision process, which the participant has to take into account when they evaluate the gap. The third column shows the available gap during the decision process from t_0 until t_{end}. It gives information about the final gap the participant accepts or rejects.
After analyzing the raw data, the response time could be calculated using the novel method.

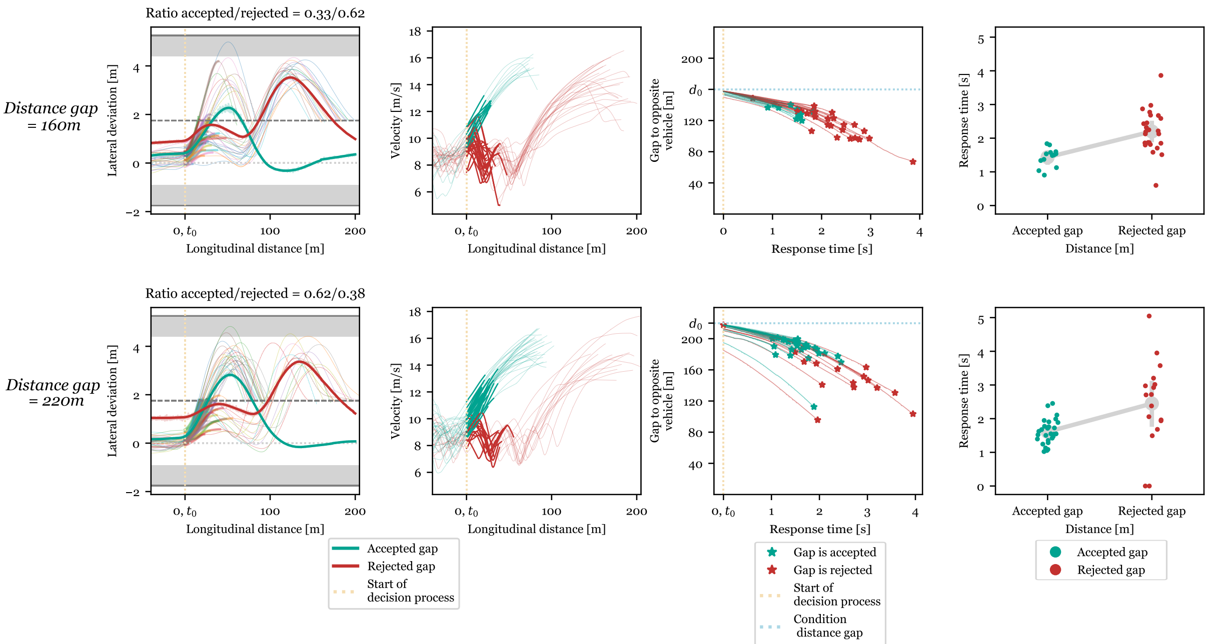

Fig. 6: Overview of the behavior of a typical participant during the decision-making process and the resulting response times for the 160m distance conditions (top row) and the 220m distance condition (bottom row). On the left the lateral deviation for accepted and rejected gap decisions are shown in green and red respectively. The faded lines are the individual trajectories. The second plots from the left shows the course of the velocity. The bold sections of the lines represent the duration of the decision-making process. In the third plots from the left the change of the distance gap during the decision-making process are shown. The stars indicate the end of the decision. 4) The plots on the right show the response times for the accepted and rejected gap decisions.

TABLE I: Outcome of statistical analysis: logistic mixed effects model and linear mixed effects model with participant number as a random effect.

	Variable	β^*	β	SE	z value	p value	97.5% 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^*	β	SE	t value	p value	97.5% 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	0 $(***)$	[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, β = unstandardized coeffcient, SE = standard error, CI = confidence interval, Akaike information criterion: *Decision* = 1312.4, *Response time* = 3881.2, *Velocity change* = 2877.1, $* : p < 0.05, ** : p < 0.01, *** : p < 0.001$

The last plots on the right show the response time for both final decisions. It can be seen that the mean response time when the gap was rejected is higher than when the gap was accepted. These results will be further studied in Section 4.2.

4.1 Gap acceptance

To analyze their influence on the gap acceptance decision, the size of the distance gap was varied and the velocity of the participant was recorded during the experiment. The percentage of accepted gaps was lower in the small gap condition than in the large gap condition, with $\beta = 0.048, z = 14.5$ and $p = 1.41e{-47}$ (see Table I) which is visualized in Figure 7. Individual drivers show the same behavior. Some participants accepted or rejected all the gaps, regardless of the condition, but no participant showed an opposite relation between the amount of accepted gaps and the distance conditions.

With regard to the velocity, if the participant was driving

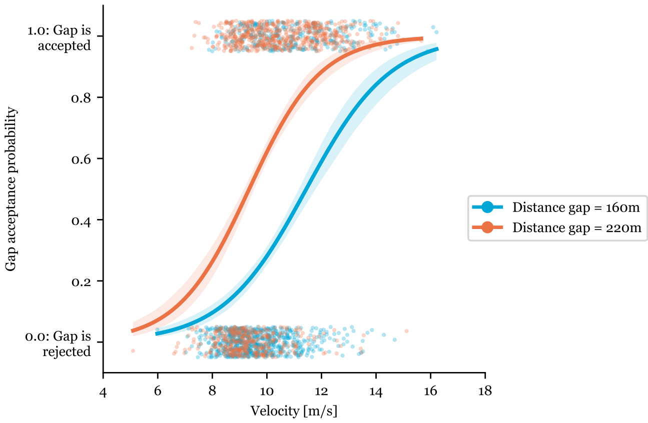

Fig. 7: Overview of the percentage of accepted gaps of all participants in both distance condition. The bold line represents the mean. The fitted lines do not match the outcome of the logistic regression, but are fitted using the Seaborn package in Python [26].

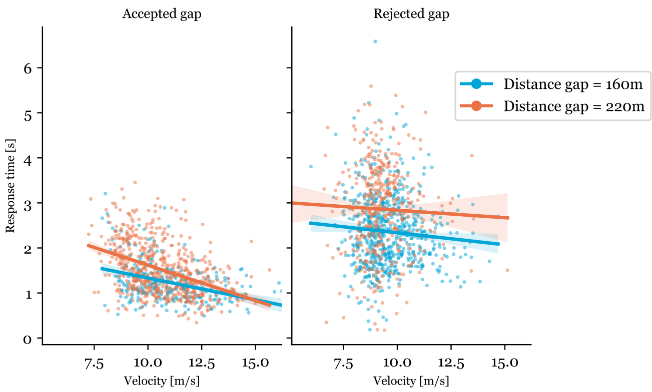

Fig. 8: Overview of the response time of accepted gaps of all participants in both distance condition. The bold line represents the mean. The fitted lines do not match the outcome of the linear regression, but are fitted using the Seaborn package in Python [26].

faster at the start of the decision, the probability that the participant accepted the gap increases significantly ($\beta = 0.84, z = 6.48, p = 9.51\text{e}{-11}$). This relation is the same in both conditions, but for the same velocity the probability that the gap was accepted is significantly higher in the large distance condition than in the small distance condition. For example, a velocity of $10m/s$ leads to a probability of 0.25 in the small distance condition, but to a probability of 0.6 in the large distance condition. Figure 7 shows the distribution of the velocity of the participants among the accepted and rejected gaps with a fitted line to illustrate the relation.

4.2 *Response time*

The response time is calculated differently depending on the outcome of the decision. Therefore, the response time will also be analyzed separately for the outcome of the decisions.

The response time when the gap was accepted is significantly

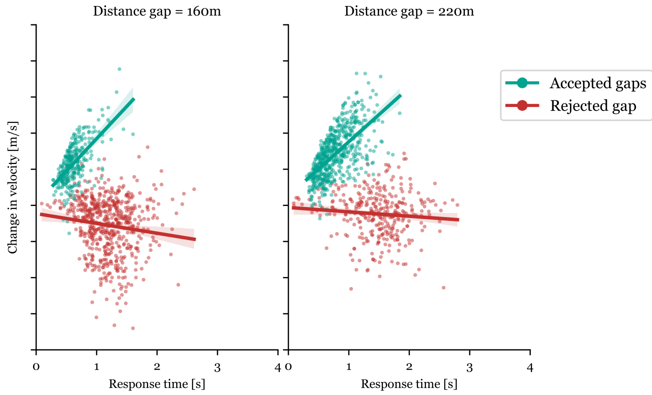

Fig. 9: Overview of the change of the velocity during the decision processes of accepted and rejected gap decisions in both distance conditions. The bold line represents the mean. The fitted lines do not match the outcome of the linear regression, but are fitted using the Seaborn package in Python [26].

lower than when the gap was rejected, with an average difference of $0.7s$ ($\beta = -0.66$, $t = -13.4$, $p = 4.86\text{e}{-39}$) (see Table I). The distance condition also positively influences the response time ($\beta = 0.0042, t = 6.98, p = 4.03\text{e}{-12}$). So, when the distance gap was larger, the response time increased by $42ms$ per $10m$. Not all participants showed this behavior, some participants had shorter response times when the distance gap was larger.

When analyzing the velocity, it was found that the participants' velocity has a negative effect on the response time ($\beta = -0.092$, $t = -5.76$, $p = 1.03\text{e}{-8}$). So, when the participants drive faster, their response time decreases with -92ms per $1m/s$. These results are visualized in Figure 8.

4.3 *Velocity change*

As can be seen in the response time results, the participants spend some time in each trial deliberating on the available gap. To analyze their behavior during the decision-making process the difference in velocity at the start and end of the decision process was calculated. A significant difference could be seen in the velocity profiles during the decision processes leading to accepted gap and rejected gaps ($\beta = 4.02$, $t = 50.0$, $p = 0$)(see Table I). When the gap was accepted the 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, with a difference of approximately $4m/s$ (see Figure 9. For some participants the mean change in velocity was negative for the rejected gaps, indicating that they decreased their velocity during the decision process. The distance gap had a relatively small influence on the change in velocity ($\beta = 0.0062$, $t = 6.12$, $p = 1.6\text{e}{-9}$).

5. Discussion

In this study a method was developed to measure the response times of the decisions during overtaking. The method was applied in a driving simulator experiment, in which the effect of the distance gap and the velocity of the driver on the gap acceptance decision and response time was analyzed. Furthermore, the change of the participants' velocity during the decision process was analyzed. In this section, the developed method and the experimental results will be discussed.

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 a few exceptions. The method was therefore applicable to both rejected and accepted gap decisions, which has not been done before.

The assumptions that have been made 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 et al. [2] measure 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 lanedivider. 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 divided in aborted gaps and rejected gaps [18]. 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 research could potentially be aborted gaps. When the manoeuvre is aborted the driver had already started their overtaking manoeuvre, which could also explain some of the longer response times in the case of 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, in theory, be measured. However, for the method for measuring response time it is assumed that the driver has a desire to overtake. This was realized in the experiment by instructing the participants to overtake before or after the oncoming vehicle. So, 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 et al. for lane changes [27].

An evident next step would be to use this method for measuring the response time and to analyze the data using an evidence accumulation model. As already mentioned before, research has shown that evidence accumulation models together with response times and decision data can unveil the course of the decision-making process [14].

5.2 Experimental results

As explained before, most previous research initiatives focusing on gap acceptance during overtaking analyze the influence of various factors on the probability a gap is accepted. In line with previous research, the experiment results showed that when the distance gap was larger, the probability that a gap was accepted was also larger. The same goes for the driver's velocity. This outcome on itself is not a novel finding. However, this research contributes to current research by analyzing the outcome together with the process of the decision-making, through measuring the response time. In the following discussion I want to elaborate on the possibilities for interpreting individual decision processes, that are created by measuring the response time.

The first new insights into the decision process are given by the found relation between the response time and decision outcome with the influencing factors. The response time can give information about the underlying processes in an individual driver. For example, the response times are often analyzed in terms of speed versus accuracy, especially in two choice decisions [28] [16]. This can give an indication about how an individual comes to a conclusion and his or her driving style. A more risk-averse driver would prioritize accuracy (or in this case safety), while an impatient driver might prefer speed. In this trade-off it is assumed that fast responses tend to be less accurate, because the decision-maker takes less time to evaluate the choices [29]. This is especially the case for decisions in which the safety is crucial, as is the case during overtaking [28].
But, the driver is not free to deliberate as long as they want, as the oncoming vehicle in the overtaking situation causes a time limit, affecting the speed-accuracy trade-off. The driver has to respond before it is too late, while also safely and accurately estimating the gap.

When interpreting the results presented in this paper, the speed-accuracy trade-off can be used to explain individual behavior within a participants. For example, if a participant who has a higher overall probability of accepting the gap in both conditions and shorter response times also drives faster, this participant has a preference for fast and thus less accurate responses. The imposed time pressure can help to unveil individual preferences in the speed-accuracy trade-off. The driver simply has less time to deliberate, making the decisions more intuitive.

But, the speed-accuracy trade-off is not the only way to analyze the results. The difficulty of a decision has also been shown to affect the response time. For example, the intensity of the visual information can determine the difficulty. The intensity of visual information can in this case be linked to the distance of the oncoming vehicle [30]. The current results show shorter response times when the distance gap was smaller. This could indicate that it was easier to estimate the distance of the oncoming vehicle and whether the gap was sufficient to overtake, due to the fact that the vehicle was closer.

When comparing the possible interpretations of the response times using time pressure and the complexity of the decision, it is difficult to decide which process dominates. Are the larger response times for the larger distance condition explained by the lower time pressure or by the difficulty of the decision? Analysis of the velocity could aid in further understanding the results. It was found that response times decreased when the participants had a higher velocity at the start of the overtaking situation. This could be caused by the increased time pressure because the time to arrival between the ego and oncoming vehicle is shorter. This corresponds to the assumption that increased time pressure leads to shorter response times. If this is then compared to the decision outcome and the size of the distance gap, conclusions can be made about the internal speed-accuracy trade-off of this participant.
With regard to the complexity of the decision, this is still difficult to say. Higher velocity could simplify the decision in the case of accepting the gap, as it is easier to overtake the lead vehicle. But the higher velocity could also complicate the decision. If the driver is tending towards rejecting the gap, due to a small distance gap, but they are driving fast, their high velocity requires them to sufficiently brake and return to their original position. This difficult manoeuvre could cause dangerous situations. The possibility of danger can result in hesitation, which causes longer response time. However, additional research needs to be done to understand what factors influence the complexity of a decision.

Bias also plays a role in decision-making [28]. A bias can be caused by personal preferences, but also due to the current situation. Because the participants' velocity is measured at the start of the overtaking situation, so before the decision, it could give an indication of a situational bias. The increased velocity could cause a certain bias towards accepting the gap. The other way around, a lower velocity could cause a tendency towards rejecting the gap. This bias could lead to the decision-maker lowering their standards for accepting the gap and responding faster, explaining the response time. This phenomena of lowering the standards for a decision due to physical constraints has been shown to occur in gap acceptance decisions [12].

The course of velocity was also studied during the decision process. After the overtaking situation has started and the driver has to make the gap acceptance decision, a driver still needs to continue driving safely. The response time measurement created a possibility to study how the initial velocity changes. When analyzing the change of the velocity during the decision process it was found that the participants started accelerating or decelerating during the decision process leading to accepted or rejected gaps respectively. So, the participants were already adapting their speed during the decision process. This could mean that while a driver is evaluating the gap he is developing a tendency towards either decisions and responding to this tendency by preparing his speed. A possible explanation is that the decision process does not consist of a single perception process followed by a reaction, but of parallel perceptions and reactions. It could be that the driver is simultaneously deliberating the gap acceptance decision and their current velocity.
The increased tendency towards either decision has been addressed in research on decision-making processes using evidence accumulation models. The preferred decision simply gains more evidence than the other decision. However, the driving behavior adaptation during the decision process has not been addressed and should be further studied.

The previously discussed analyses illustrate how response time is capable of explaining multiple aspects of driving and decision-making behavior. With the measurement of response time many facets of the course of a decision-making process can be unveiled. With the use of the evidence accumulation models in combination with the response time, research on the decision-making process during overtaking can be extended.

Limitations of the experiment and recommendations

A limitation in the analysis of the experimental data is the fact that the use of repeated measures is neglected. Response time research have shown that the use of multiple measures of response for the same decision can cause a learning effect in the decision-making [14]. The first time the participant is presented with a decision they might make an initial fast response under the time pressure. When they start to recognize the situation after repeating the same decision, they will make a more deliberated response, as they have had more time to evaluate the situation. The participant can also develop a bias towards a decision. It could be interesting to look at the differences in response time and decision outcomes over the course of a whole experiment. It could give an indication of the influence of time pressure and the way the participant deliberates speed versus accuracy.

Another limitation relates to the velocity of the oncoming vehicle. As explained in Section 3.3 the oncoming vehicle started driving with a low acceleration, so it appeared to be standing still. However, the oncoming vehicle did have an acceleration, so their velocity increased during the decision process. This could have potentially influenced the results, but has been neglected in the data analysis.

The addition of a controlled varying time gap could further specify the relation between the size of the gap and the decision and response time. The time gap can be controlled using the velocity of the oncoming vehicle. While the time gap is now varied through the velocity of the participant and the two distance conditions, a controlled time gap could give more specific information. This also gives the opportunity to compare the sizes of the time gap, in a way that is done for the distance gap. Current literature has already shown the influence of the time gap on the probability of accepting the gap [4].

Lastly, the use of a driving simulator has influenced the results. As described by Karimi et al. [20], drivers behave differently in a driving simulator and take more risks. However, they conclude that results on overtaking manoeuvres obtained in a driving simulator are valid.

6. Conclusion

The aim of this research was to analyze the influence of the size of the distance gap and the driver's velocity on the response time of the gap acceptance decisions during overtaking. The response time was measured using a method proposed in this paper, using the position of the ego vehicle and the surrounding vehicles, and the decision outcome. The method was the first to include the response time of rejected gap decisions. This method was then applied in a driving simulator experiment to measure the response time. In this experiment the size of the distance gap between the participant and oncoming vehicle was varied, to measure the influence of distance on the gap acceptance decision and response time. To measure the influence of the drivers' velocity, the velocity was measured at the same moment as the distance. Once the response time was calculated, the actual behavior during the decision process was analyzed, with regard to the velocity. This was done by calculating velocity change between the start and end of the decision process.
From the studied experiment data, I can conclude the following:

- The proposed method of measuring the response time allows to measure the response time of gap acceptance decisions during overtaking. With this measured response time the effects of influencing factors can be unveiled.
- The size of the distance gap and the drivers' velocity significantly influence the probability of accepting the gap. When the size of the gap is larger, the probability increases. The probability of accepting the gap was also higher when the driver was driving faster.
- The response time is significantly linked to the outcome of the gap acceptance decision, the response time is on average $0.7s$ longer for rejected gaps compared to accepted gaps.
- The response time increases significantly with the size of the distance gap, with an increase of $42ms$ per $10m$. The response time decreases significantly with the velocity of the ego vehicle, with a relation of -$92ms$ per $1m/s$.
- During the decision process the drivers' velocity does not stay constant. During the decision process leading to an accepted gap decision, the drivers increase their velocity and during the decision process leading to a rejected gap, the drivers decrease their velocity. The difference between the change of the velocity for accepted and rejected decision processes was $4m/s$.

This study shows the importance of including the response time in research into gap acceptance decisions during overtaking. My results can be used to predict decision outcomes and response times using evidence accumulation models. Predicting decision outcomes can help us understand the errors that drivers make while overtaking, so we can increase the safety on the road.

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A

Informed Consent Form

Informed Consent Form in a driving simulator study

Researchers:
Annemartijne Sevenster – MSc. student
E-mail: a.l.a.sevenster@student.tudelft.nl
Tel: +31 (0)6 13323431

Prof.dr.ir. D.A. Abbink – Supervisor
E-mail: d.a.abbink@tudelft.nl

Dr.ir. A. Zgonnikov – Supervisor
E-mail: a.zgonnikov@tudelft.nl

Dr.ir. H. Farah - Supervisor
E-mail: h.farah@tudelft.nl

This document describes the purpose, procedures, benefits, risks and possible discomforts of a driving simulator study. It also describes the right to withdraw from the study at any time in any case. Before agreeing to participate in this study, it is important that the information provided in this document is fully read and understood.

Location of the experiment
TU Delft, Faculty of Mechanical, Maritime and Materials Engineering (3mE)
Cognitive Robotics Lab (F-1-490)
Mekelweg 2, 2628CD Delft

Description of Experiment:
In this experiment you will be asked to perform a driving task in a virtual driving simulator. In each trial, you will be asked to drive in an urban location. The experiment will take approximately 1 hour to complete.

In order to participate in this research, it is necessary that you give your informed written consent. By signing this page you are indicating that you understand the nature of this research and your role in it and that you agree to participate in the research.

Task instructions: During the entire track drive as you normally would. You are expected to drive on the right-lane unless the traffic situation requires you to drive on the left-lane.

Confidentiality: The collected data in this experiment is kept confidential and will be used for research purposes only. The data will also be anonymised i.e. you will be identified by a subject number.

Right to refuse or withdraw: Your participation is strictly voluntary and you may withdraw from or stop this experiment at any time, without consequences.

Questions: If you have any questions regarding this experiment, feel free to contact A. Sevenster (contact details are provided at the top of this document).

Additional information regarding COVID-19: To prevent the spread of the corona virus (in compliance with the university's policy), researchers and participants in the study:

- have to be younger than 65 years
- don't have any underlying ailments that could be seen as a riskfactor for a COVID-19 infection
- don't have any complaints or symptoms that could be indicative of a COVID-19 infection
- have not been in contact with a COVID-19 patient at least 14 days before participation in the study
- take suitable protective measures if a minimum distance of 1.5 meters is not viable

- are enabled to travel outside of rush hours to and from the research location
Also, any objects or surfaces researchers and participants come into contact will be disinfected prior and after use.

Please confirm the following points before signing:

- **I understand that I am participating in human factors research;**
- **I consent that the data gathered during the experiment may be used for a MSc thesis and possible future academic research and publications;**
- **I understand that my participation will be anonymous (that is, my name will not be linked with my data) and that all information I provide will remain confidential;**
- **I understand that I will be provided with an explanation of the research in which I participated and will be given the name and e-mail address of an individual(s) to contact if I have questions about the research;**
- **I understand that participation in research is not required, is voluntary, and that I may refuse to participate further without negative consequences;**
- **I adhere to the preventative measures with regards to COVID-19 as explained above.**

By signing this form, I am stating that I understand the above information and consent to participate in this study being conducted at TU Delft.

Name: ____ *Participant ID:* __________________

Signature: ___________________________________ *Today's Date:* _________________________

B

Development of method for measuring response time

Before the experiment, two pilot experiments have been executed. In this chapter these experiments and their outcomes are discussed. The experiments were aimed at determining the correct method of measuring the response time. The response time is measured using the difference between the start of the decision and the end of the decision and the two pilots were focused on these two moments respectively.
The decision to overtake can be divided in two stages: the desire to overtake and the decision to overtake. To detect or identify the start of the decision it should also be clear whether there is a desire to overtake. In the first pilot two methods are compared to induce a desire to overtake and a start of a decision process.

B.1. Pilot 1: Start of the decision

The goal of the first pilot experiment is to verify the moment the decision process for gap acceptance for an overtaking manoeuvre starts. The experiment only aims at validating the moment. A simple pilot study with four participants is conducted.

Two initiation moments are compared and validated. These moments are based on perception - the decision process will start when a signal comes into view (in this case, appears on the screen). This is consistent with findings that gap acceptance decisions are based on perceptual cues and the underlying theories behind evidence accumulation models. So, a situation must be created in which the driver is presented with a perceptual signal which will immediately induce a desire to overtake and thus the decision process for evaluating the available gap.

Stefansson et al. [2] used a method where the driver would be induced to overtake by a slow driving lead vehicle, but the opposing lane would be blocked by a row of vehicles without any space in between to overtake. The decision process would start the moment the last vehicle in the row passed the ego vehicle. After this moment an available gap would present itself, which the driver would accept or not. Such a situation can be mimicked with a single fast vehicle (driving so fast or with such a small distance to make it impossible to overtake before this vehicle), such as done by Karimi et al. [1].
For the other initiation moment, the blocking vehicles are replaced by a sharp curve. The driver cannot see the slow driving lead vehicle while driving through the sharp curve. Once they leave the curve, they have to respond immediately to avoid a crash.
In both situations an oncoming vehicle is driving in the opposite lane, whose distance to the ego vehicle is varied.

Participants and apparatus Four participants (all male) of an age between 25 and 26, with a valid driving license, participated in the experiment. The apparatus and set-up of the pilot experiment was the same as described in the paper.

Experimental design

- The distance gap was varied.

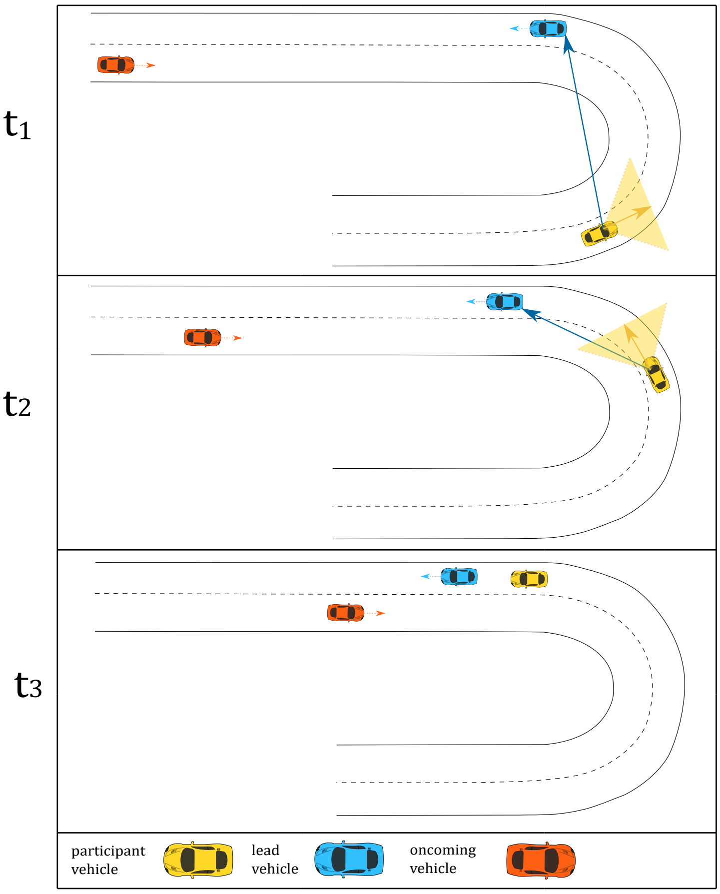

Figure B.1: Visualization of the use of a sharp curve for the start of the decision process. The yellow area shows the visual angle of the participant, which is set in CARLA. At t_1 the participant can not see the lead vehicle. At t_2 the blue line is in the yellow area, indicating the the lead vehicle is in sight. The start of the decision process would then be marked at t_2. t_3 shows the situation after the curve.

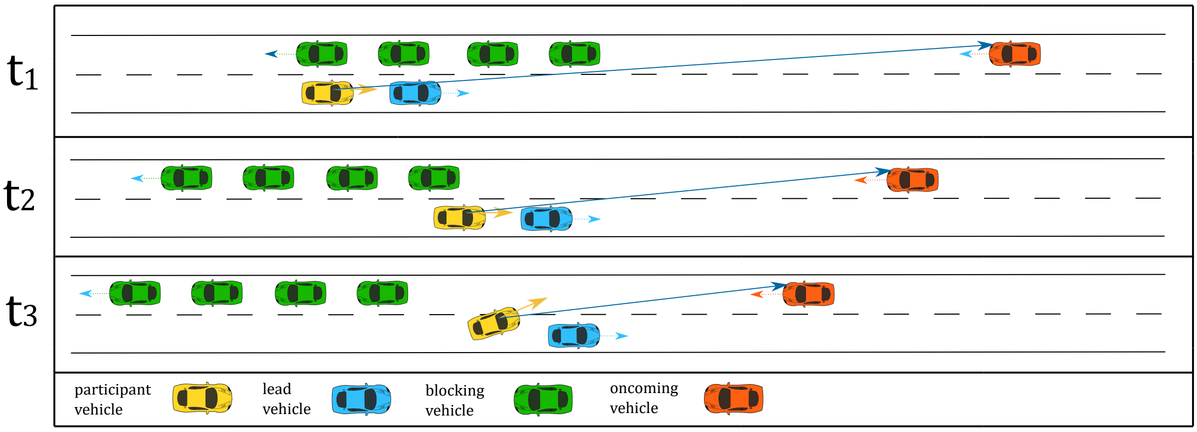

Figure B.2: Visualization of the use of a platoon of vehicles for the start of the decision process. The yellow and blue line show when the oncoming vehicle is visible for the participant. At t_1 the lead vehicle still blocks the view and the platoon blocks the opposite lane. The participant is stuck behind the lead vehicle. At t_2 the opposite lane is free and the participant could overtake. At this time the participant is able to see the oncoming vehicle and thus the available gap. The decision process starts at t_2. At t_3 the participant starts to cross the lanedivider.

- 8 trials, with 4 repetitions of the two distance conditions.

Results and conclusion

- The platoon condition showed more consistent and controlled behavior, which can be seen when comparing Figure B.3 and Figure B.4.
- In the curve condition the situation changed in a collision avoidance manoeuvre, rather than a

gap acceptance decision. This was concluded from the abrupt behaviour and the feedback given by the participants.

- The platoon condition was chosen as a method to control the start of the decision.

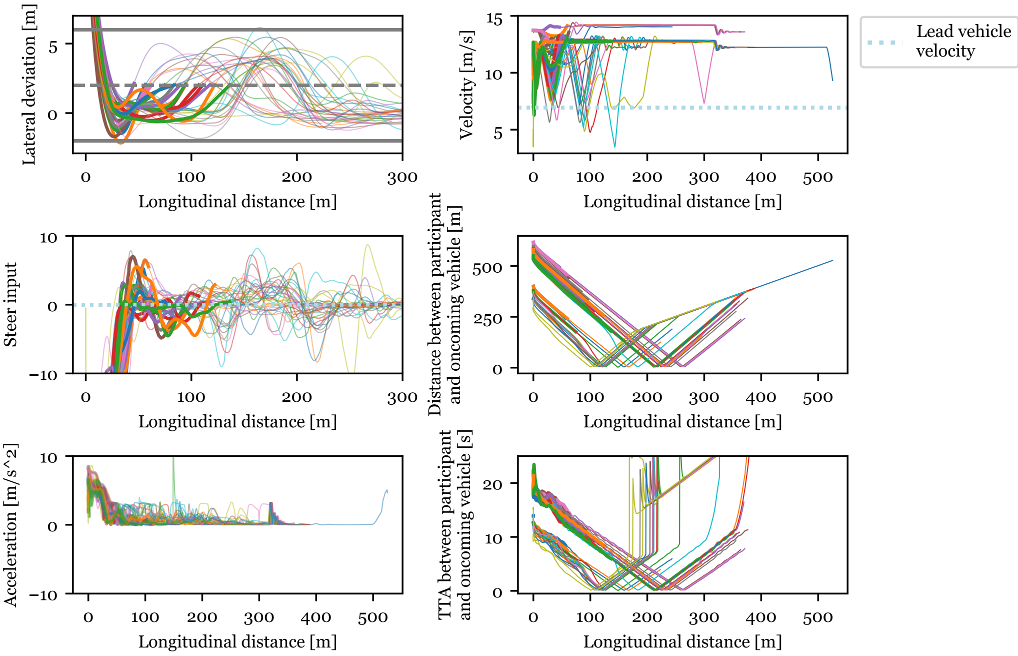

Figure B.3: Overview of data in the curve situation in Pilot 1.

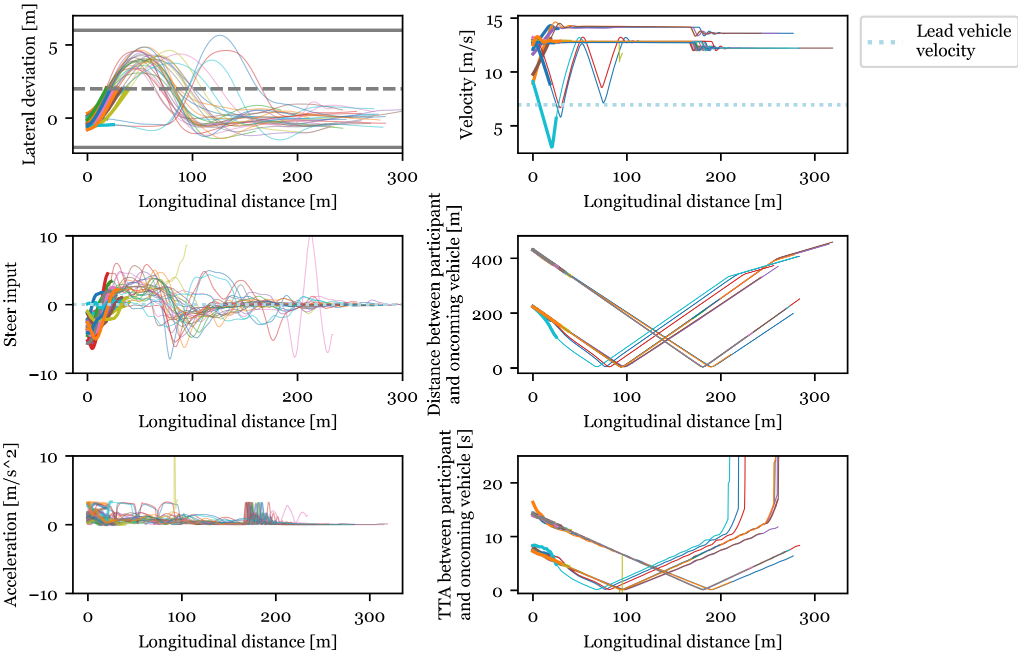

Figure B.4: Overview of data in the platoon situation in Pilot 1.

B.2. Pilot 2: End of the decision

To complete the measurement of the response time an end of the decision process has to be identified. In previous literature the end of the decision-making is identified as the moment a certain action is executed. E.g. Zgonnikov et al. [3] measured the response time for a left-turn scenario. The driver would stop at a stop sign at an intersection and had to decide to take a left turn before an oncoming vehicle or to wait after the oncoming vehicle had passed. When the driver pressed the gas pedal they marked the decision as 'turn' and marked this as the end of the decision. For the 'wait' decisions however, no end of the decision process was identified and these decisions where thus not included in the response time analysis.
The same goes for overtaking decisions, the decision process ends when the overtaking manoeuvre is initiated. This however only holds for the 'accepted' decisions.
The aim of this experiment is to further specify the use of a platoon of vehicles to control the start of the decision, as concluded in Pilot 1.

Participants and apparatus Two participants (one female and one male) of an age of 25, with a valid driving license, participated in the experiment. The apparatus and set-up of the pilot experiment was the same as described in the paper.

Experimental design

- The start of the decision was defined as the moment the participant could see the oncoming vehicle, using the visual angle.
- The distance gap was varied between 100m and 150m.
- 8 trials, with 4 repetitions of the two distance conditions.

Results and conclusion A difference was seen in the trajectories for the rejected and accepted gaps, which can be seen in Figure B.5. The results were consistent during the experiment, which is shown in Figure B.6 This led to the final development of the method for measuring the response time, where the extra peak in the rejected trajectory was used as the end of the decision process.

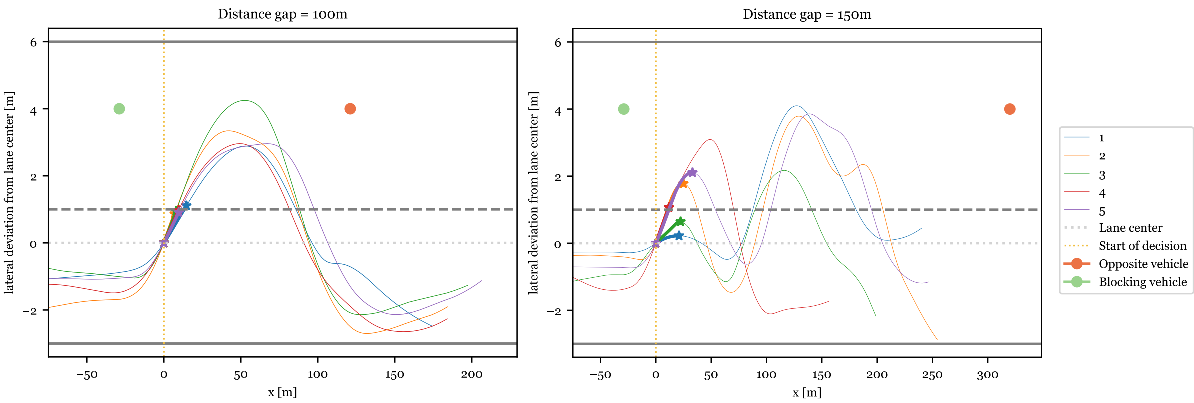

Figure B.5: The lateral deviation of the participants in Pilot 2, clearly showing the difference between accepted and rejected gaps, functioning as the basis for the end of the response time measurement. The bold lines indicate the duration of the response time, with stars marking the start and end of the decision.

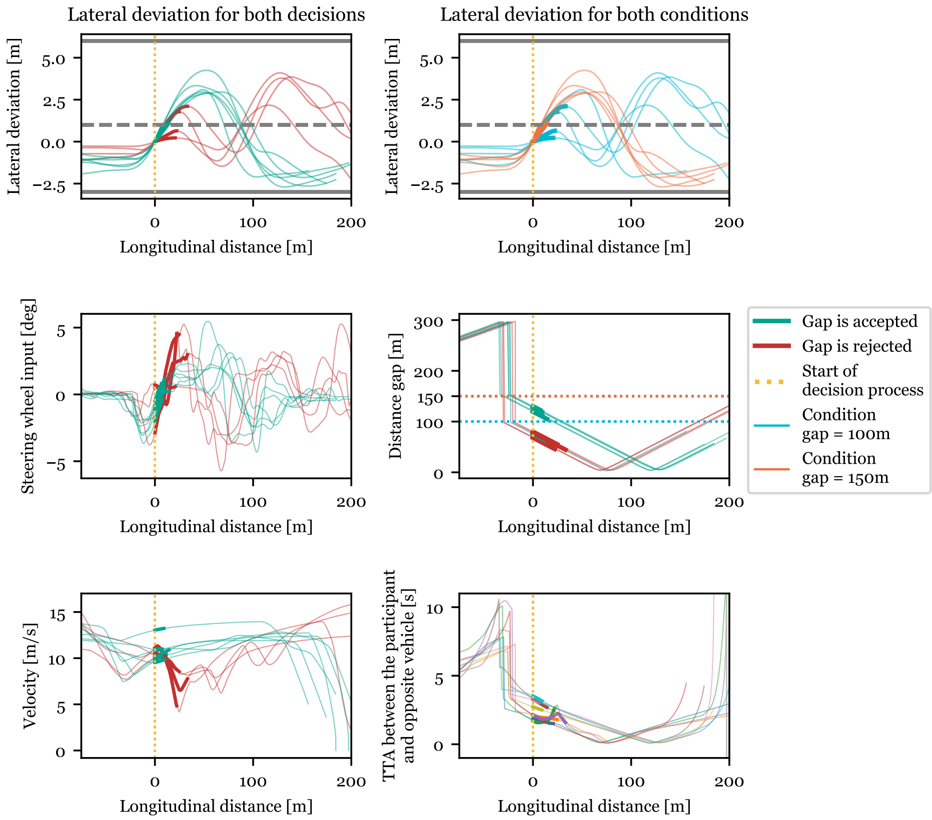

Figure B.6: Overview of data in for both conditions in Pilot 2.

C Extensive Results

This appendix contains an overview of the experimental data for each participant. The format is the same as was used for the typical participant in the paper.

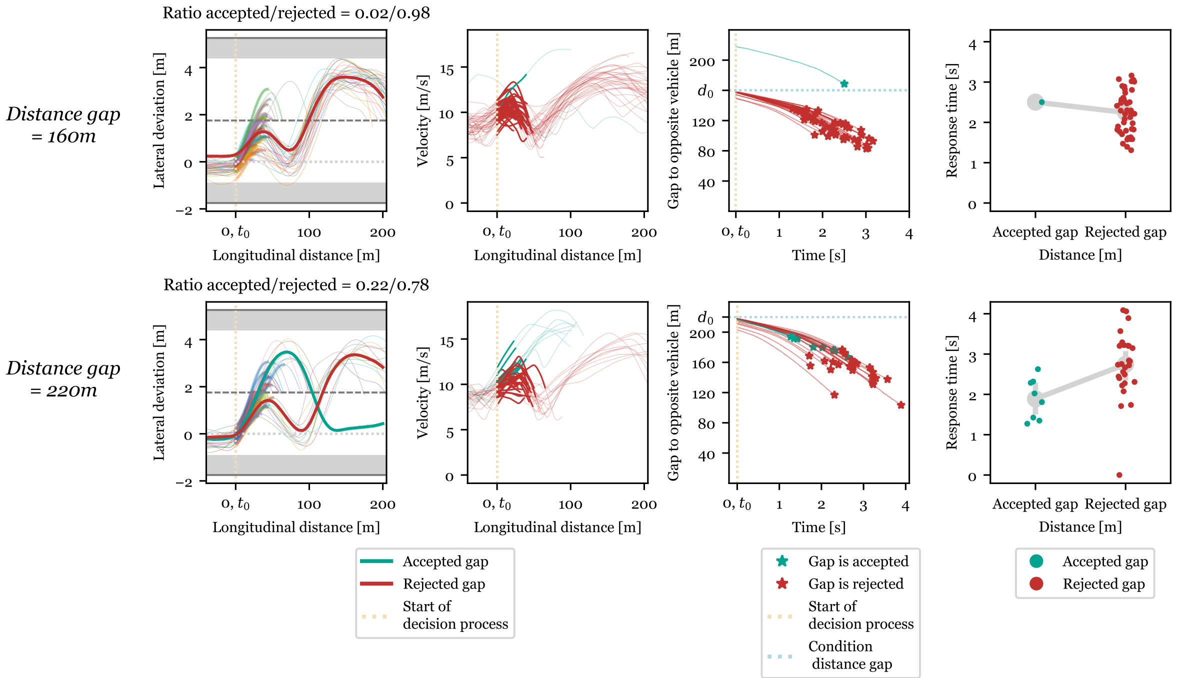

Figure C.1: Overview of data of participant 175.

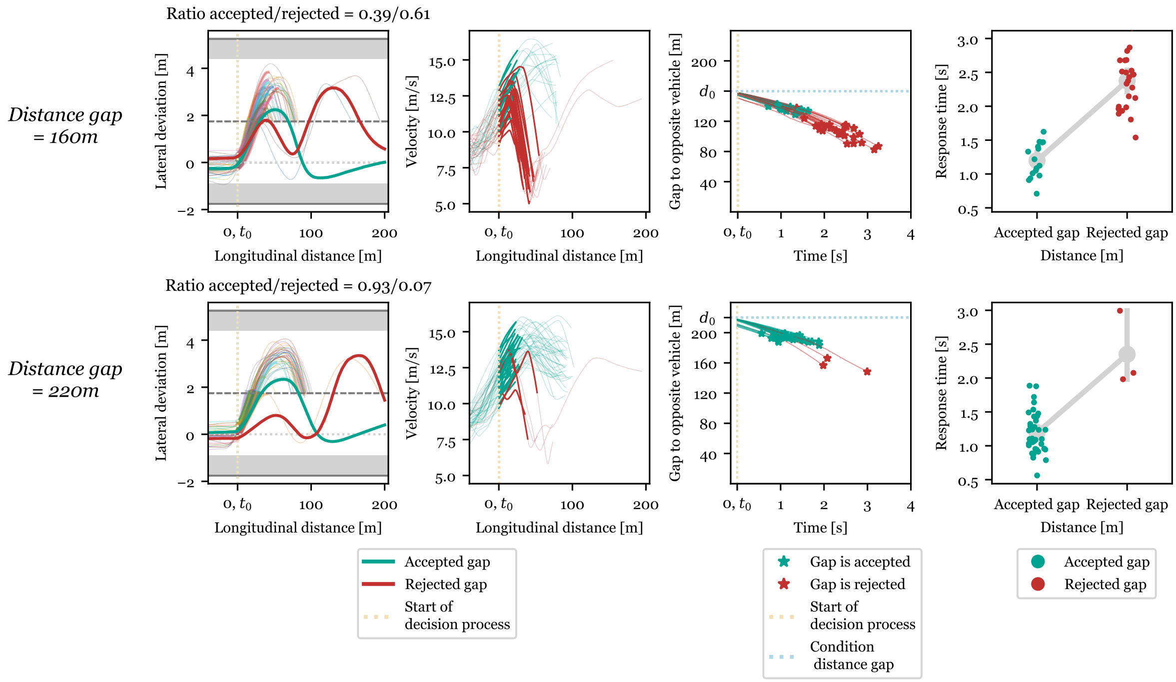

Figure C.2: Overview of data of participant 190.

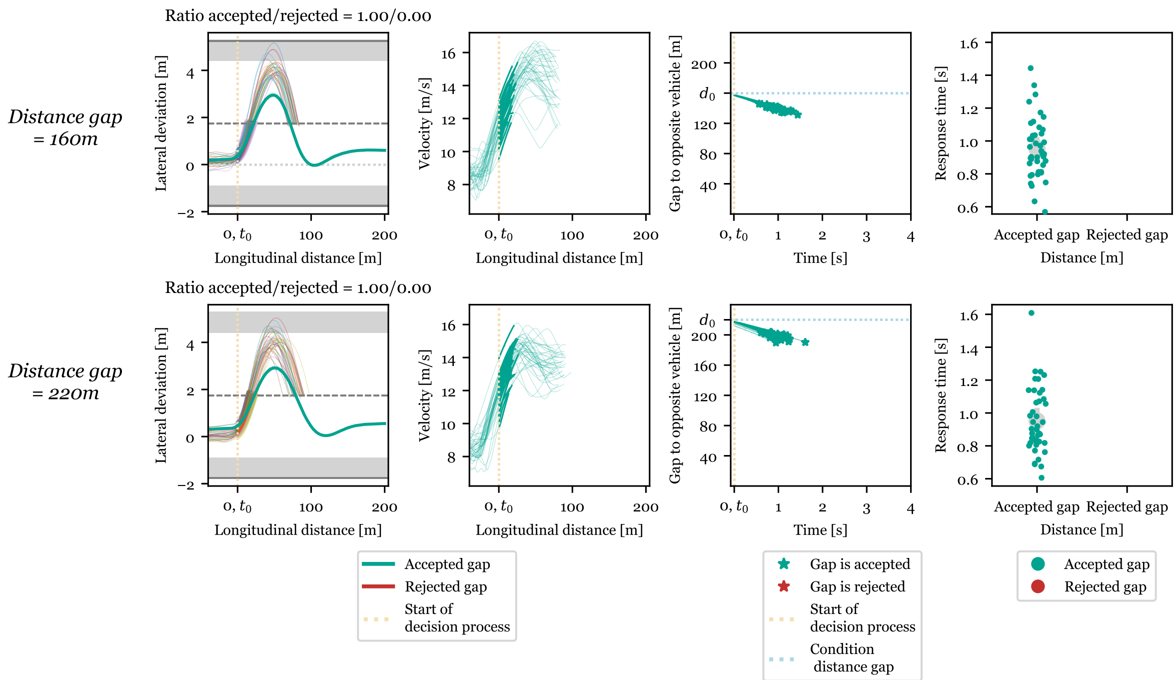

Figure C.3: Overview of data of participant 192.

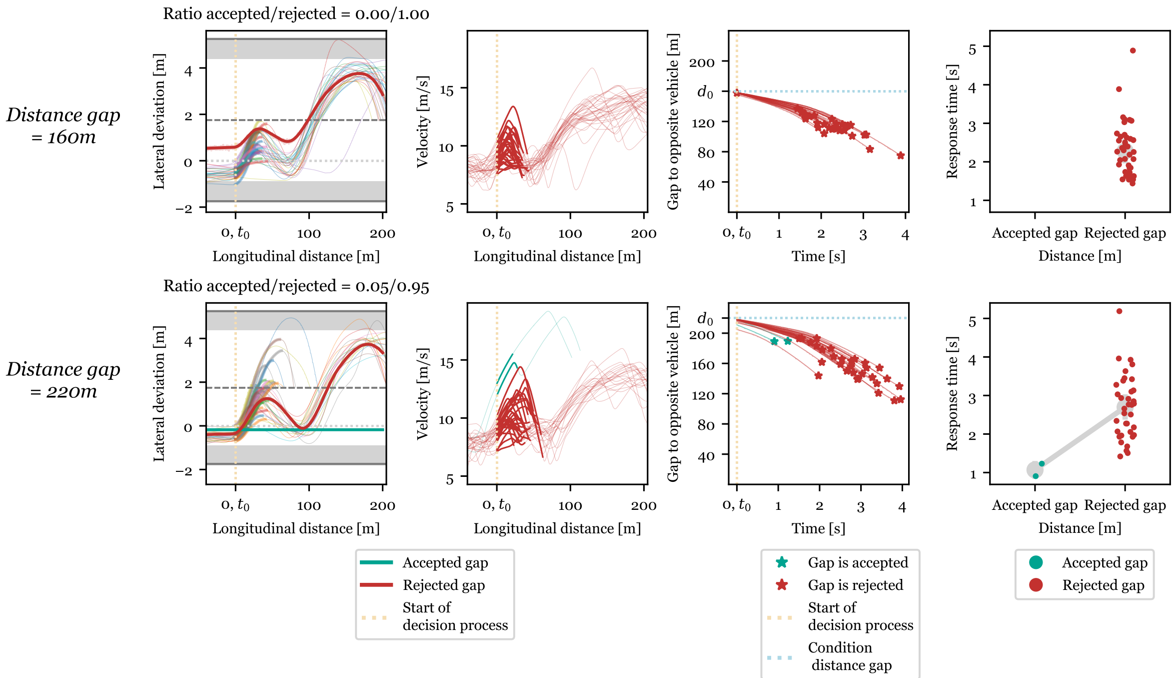

Figure C.4: Overview of data of participant 200.

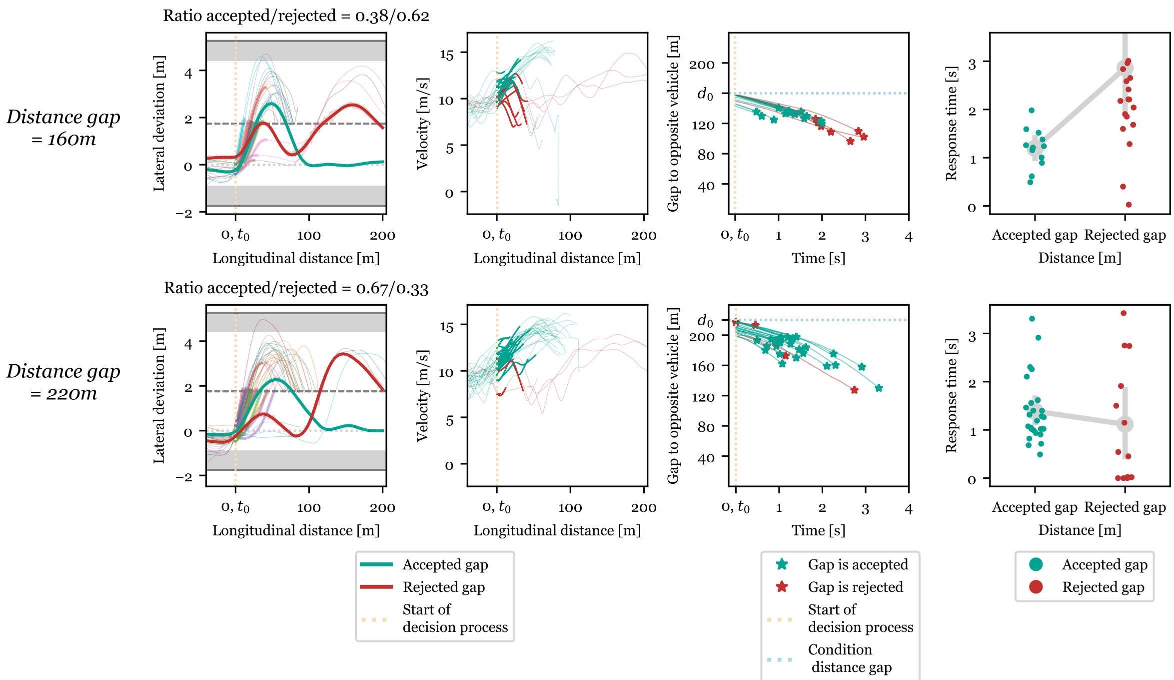

Figure C.5: Overview of data of participant 209.

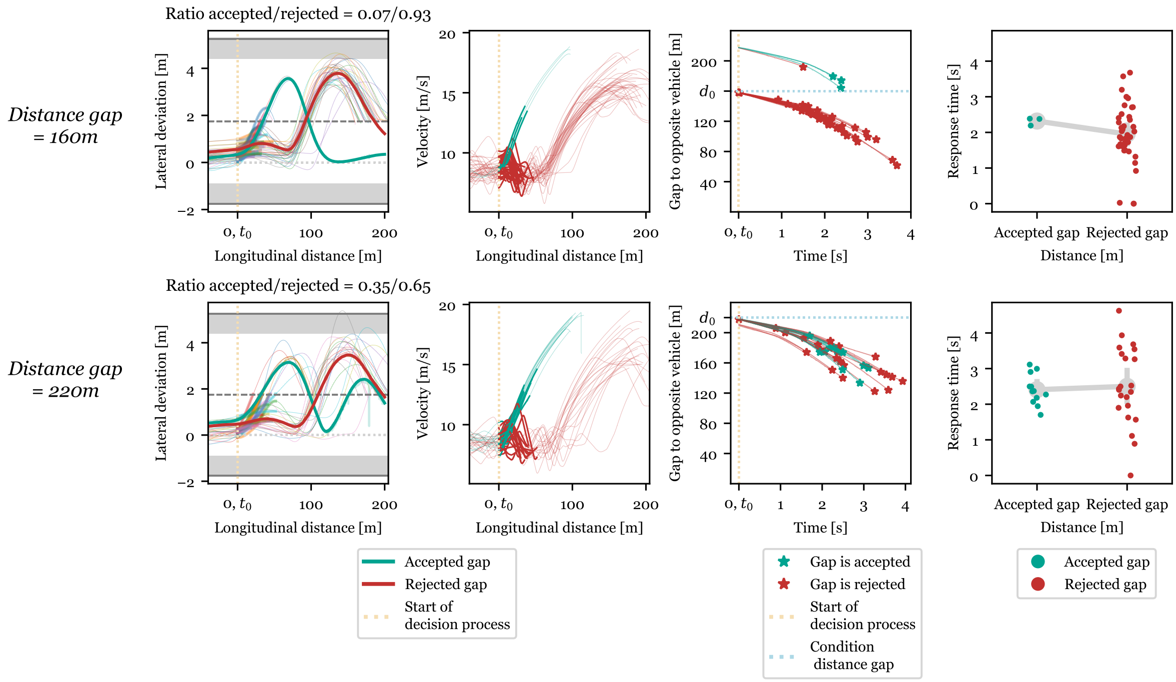

Figure C.6: Overview of data of participant 220.

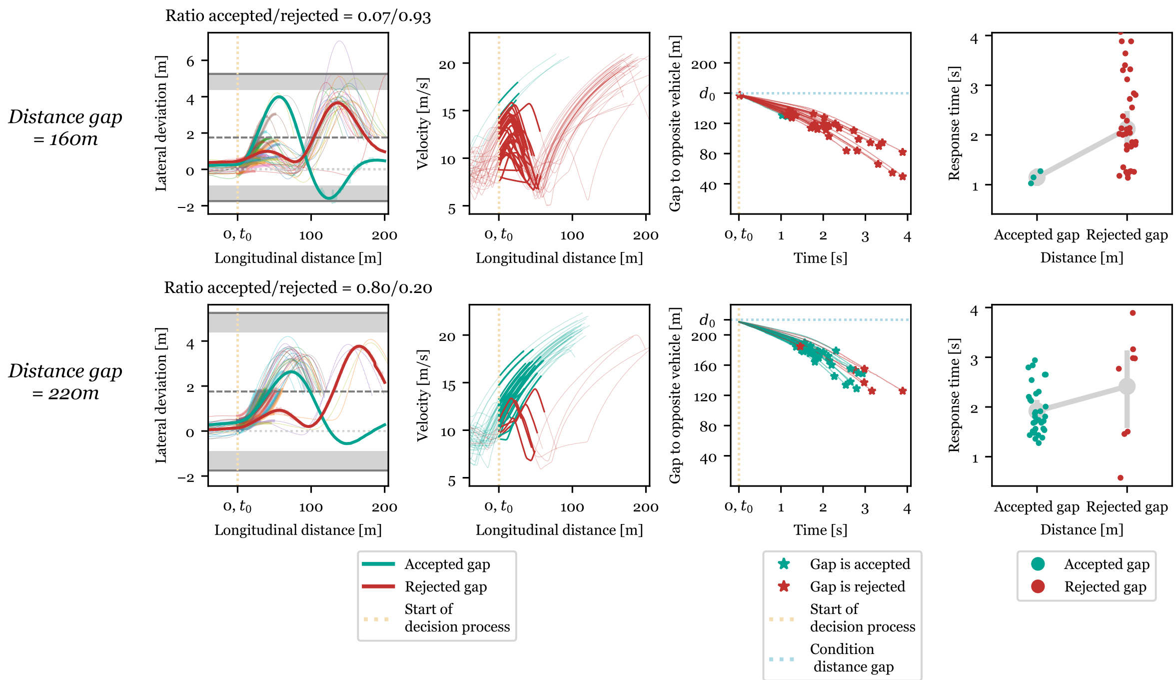

Figure C.7: Overview of data of participant 262.

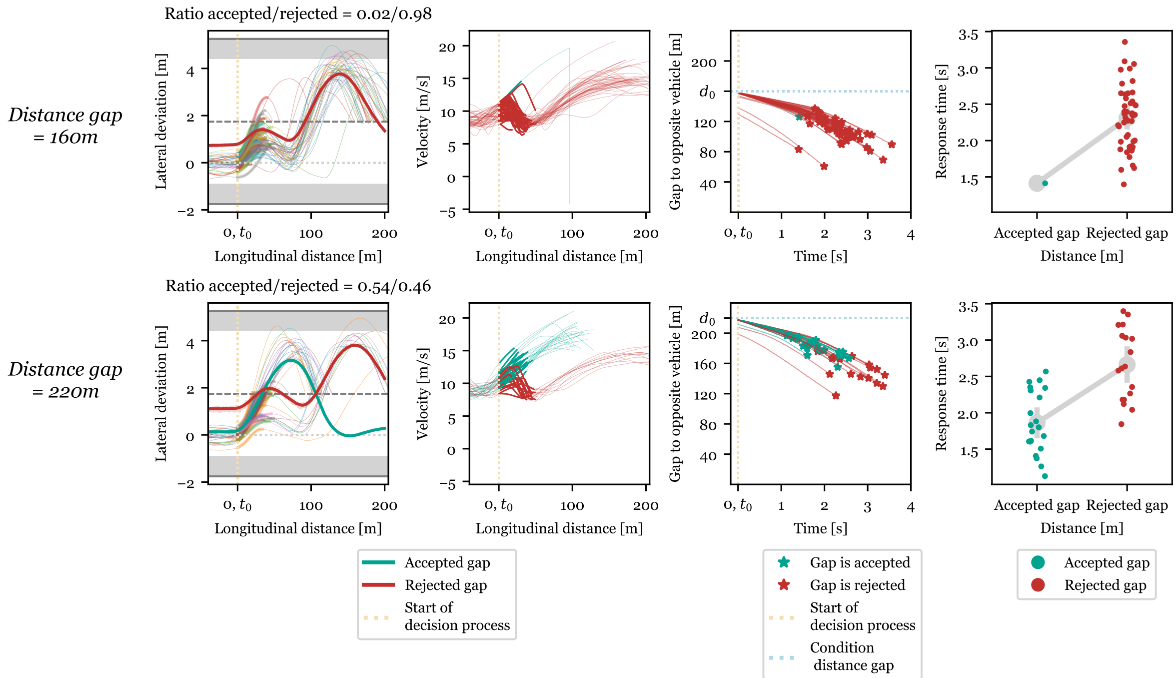

Figure C.8: Overview of data of participant 346.

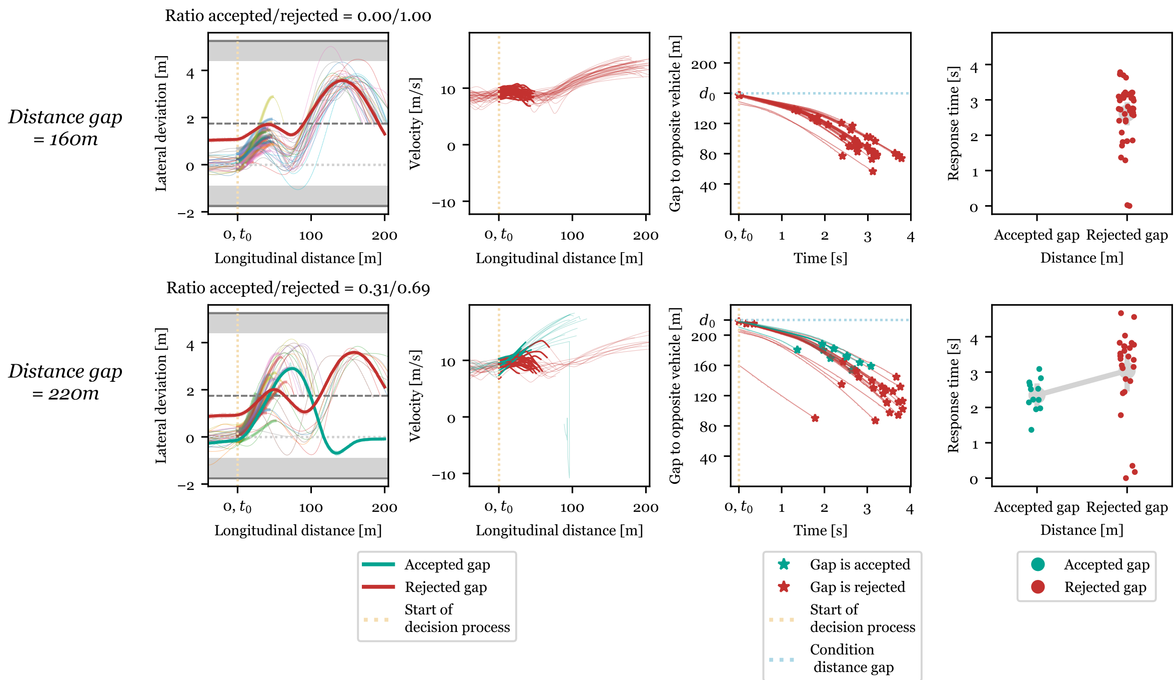

Figure C.9: Overview of data of participant 380.

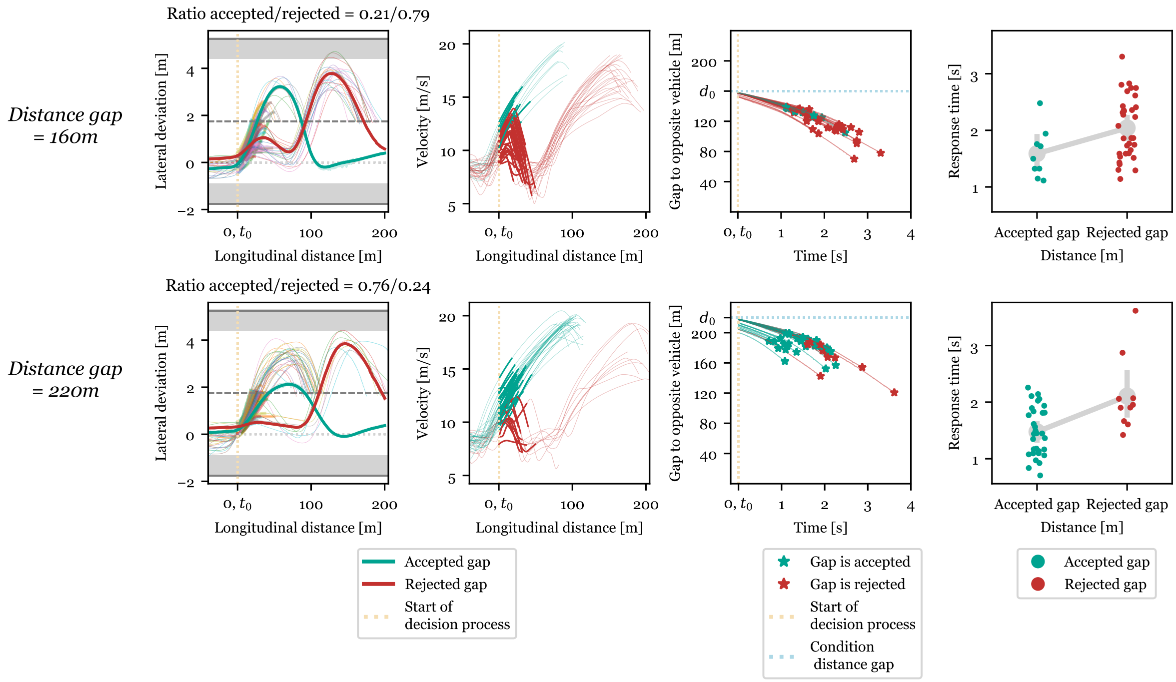

Figure C.10: Overview of data of participant 396.

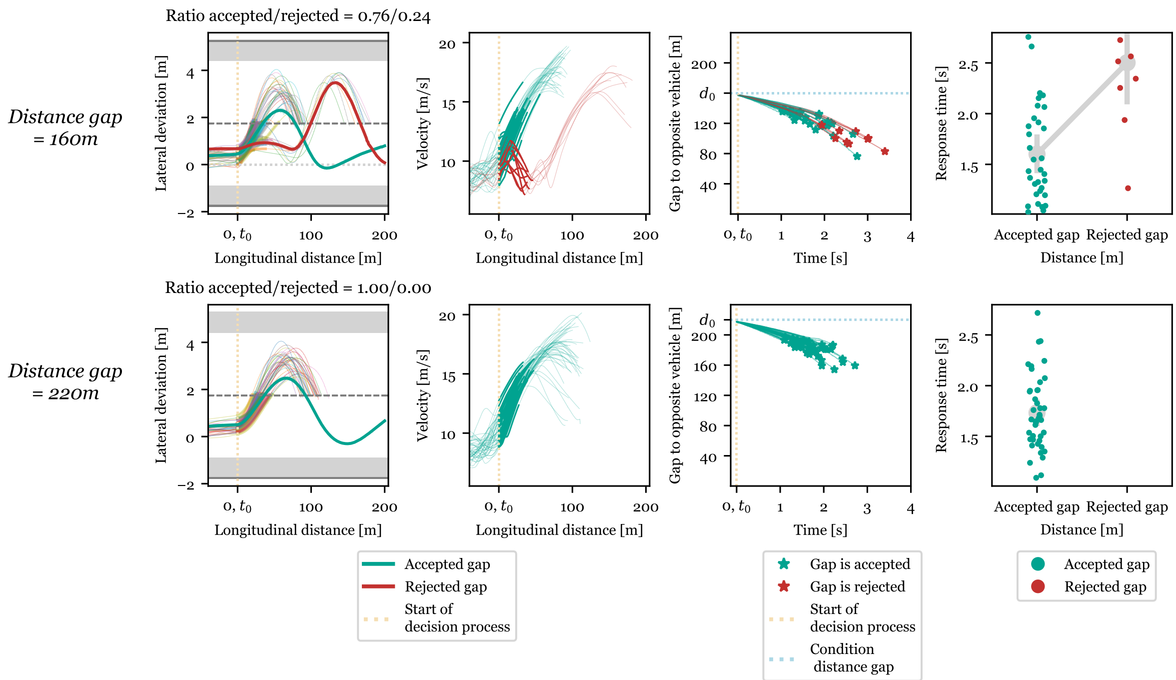

Figure C.11: Overview of data of participant 405.

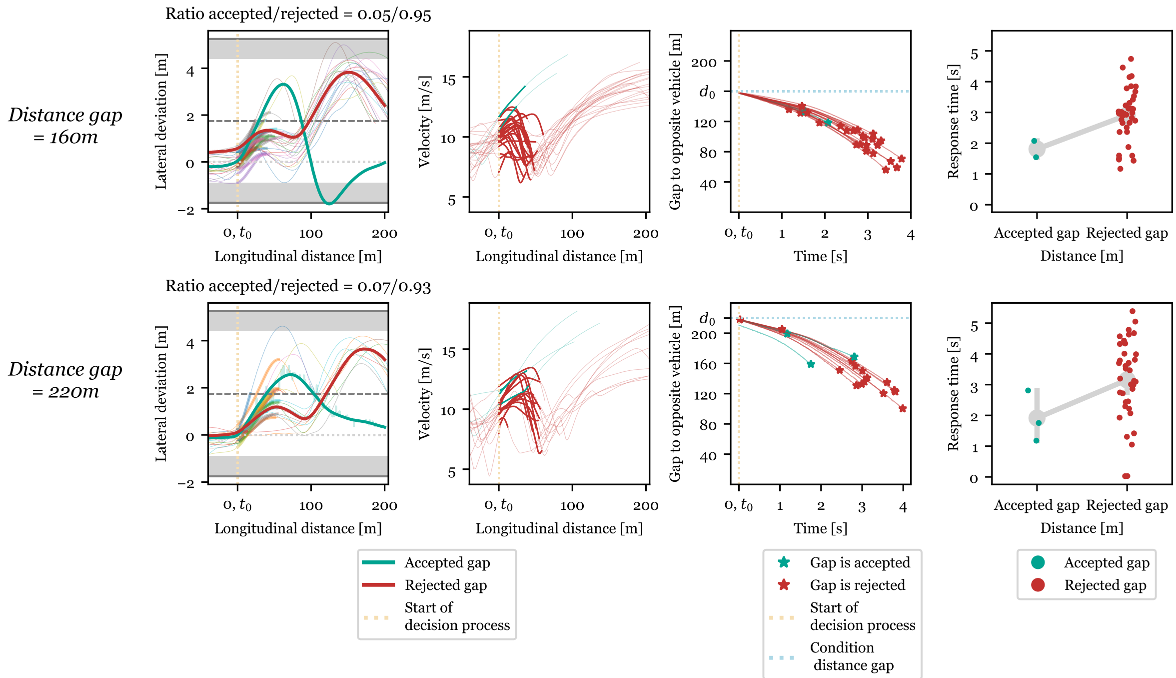

Figure C.12: Overview of data of participant 501.

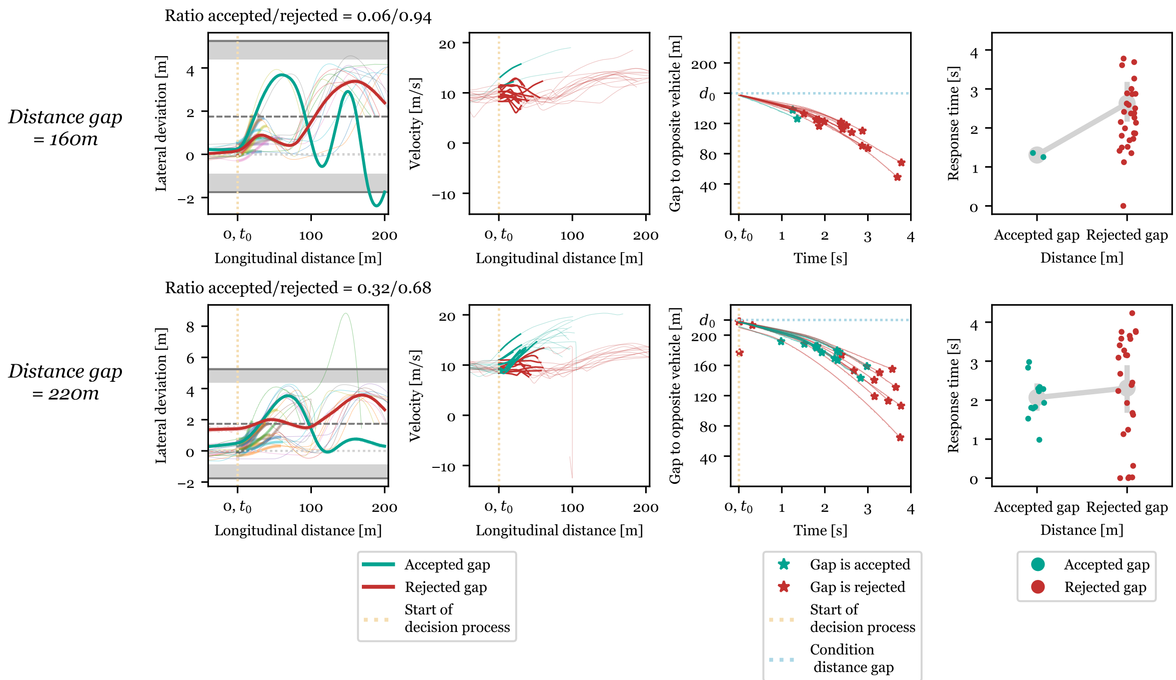

Figure C.13: Overview of data of participant 525.

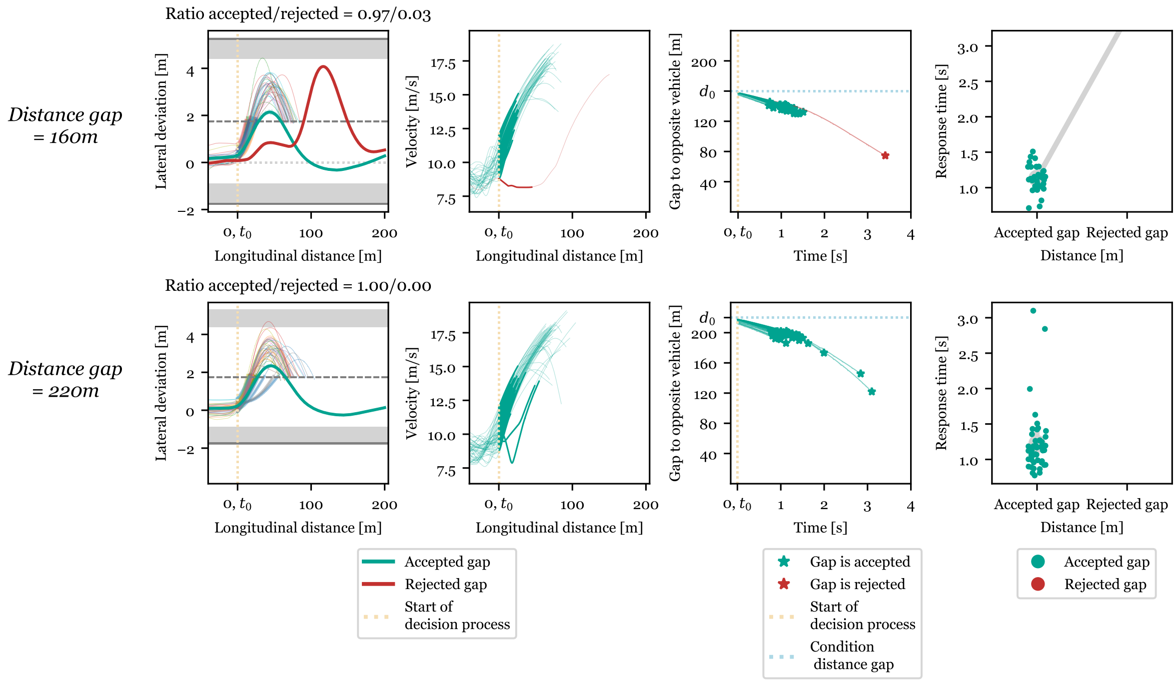

Figure C.14: Overview of data of participant 575.

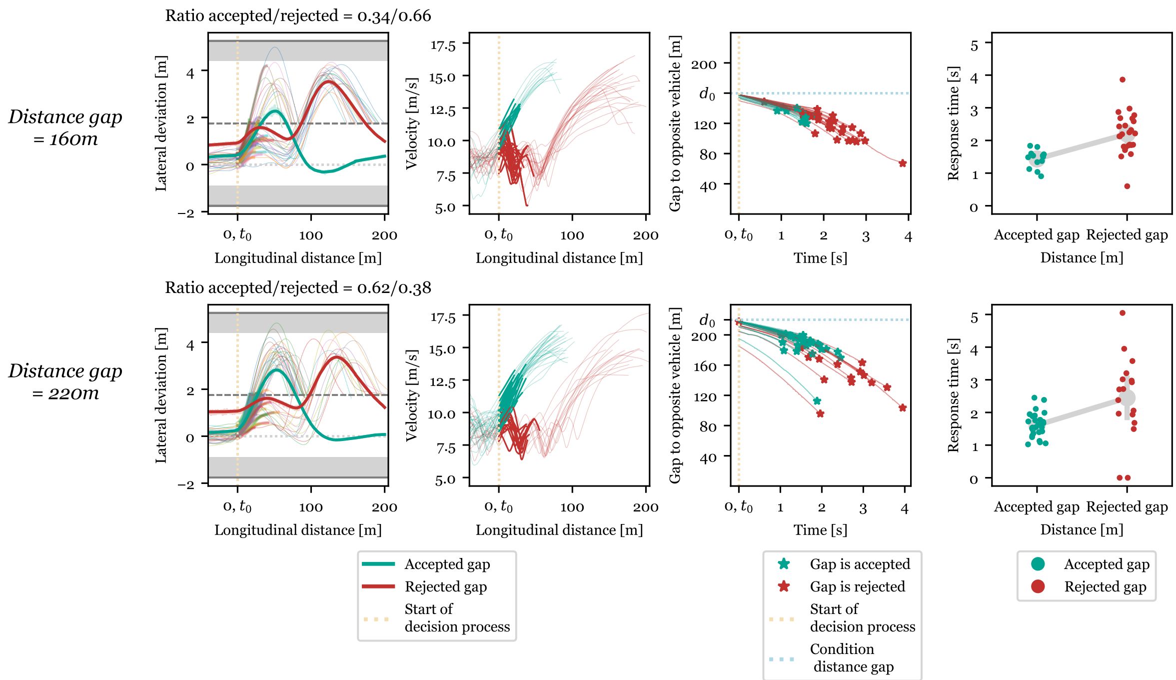

Figure C.15: Overview of data of participant 634.

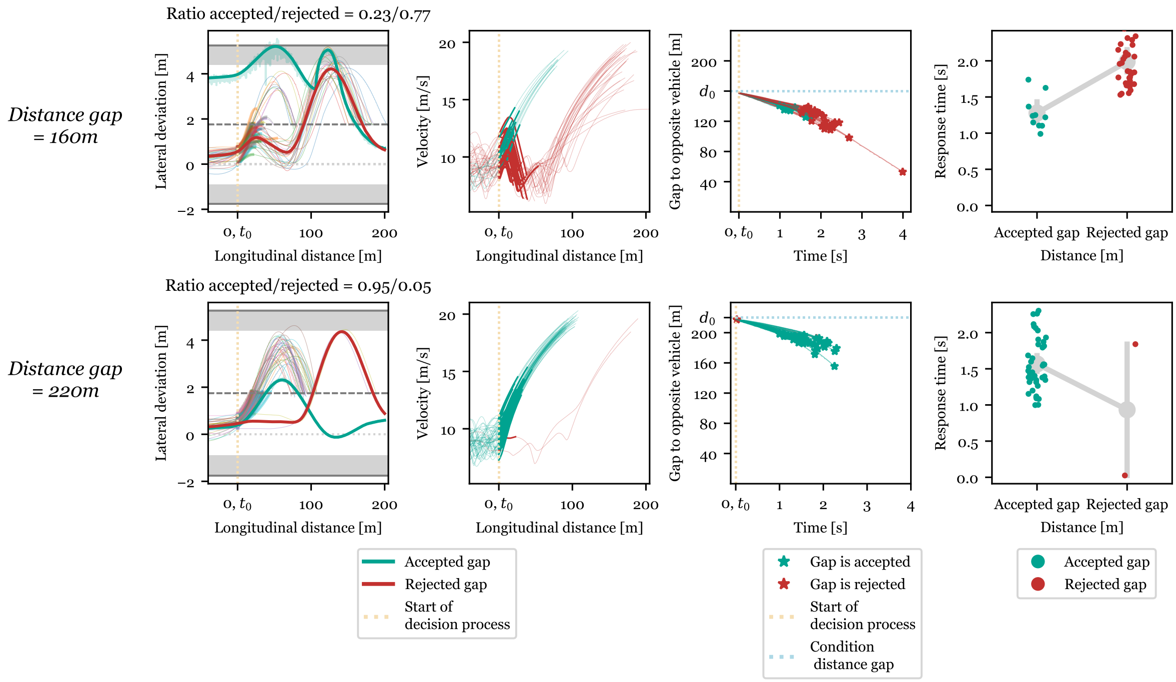

Figure C.16: Overview of data of participant 678.

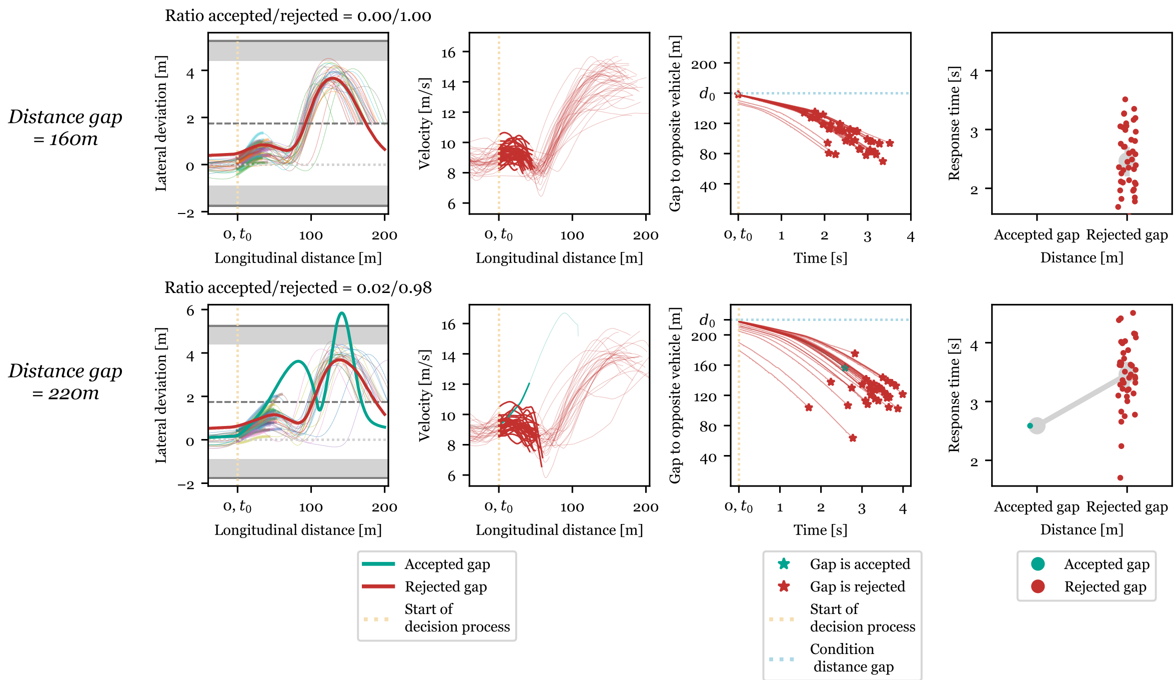

Figure C.17: Overview of data of participant 681.

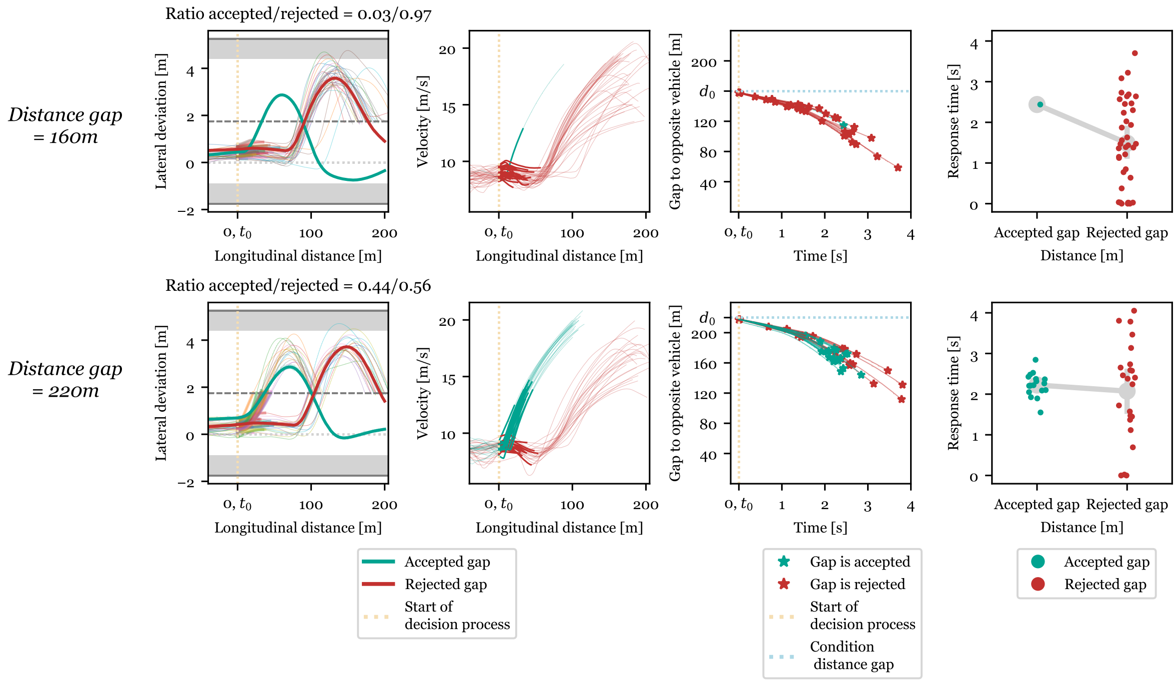

Figure C.18: Overview of data of participant 697.

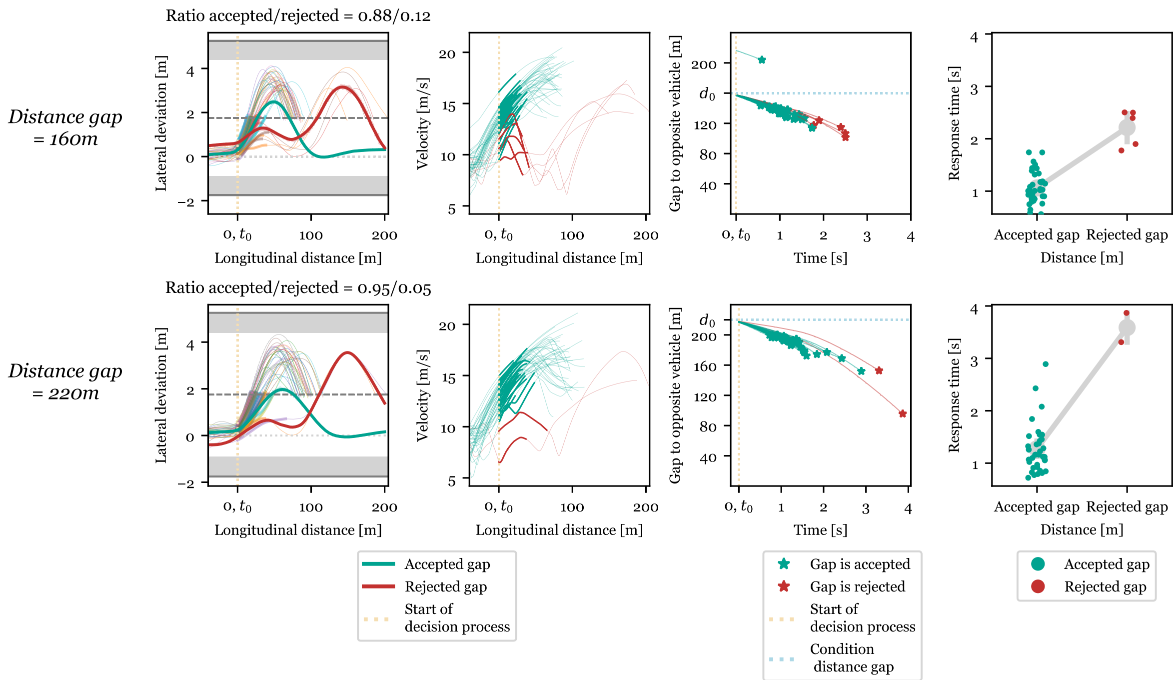

Figure C.19: Overview of data of participant 776.

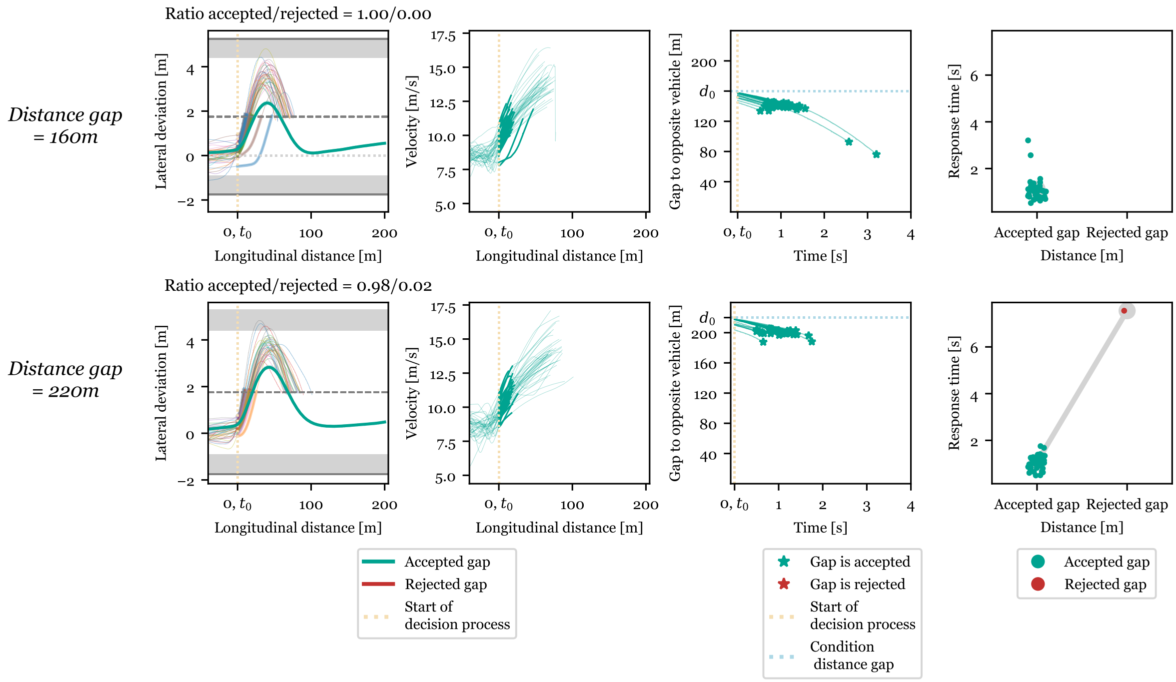

Figure C.20: Overview of data of participant 781.

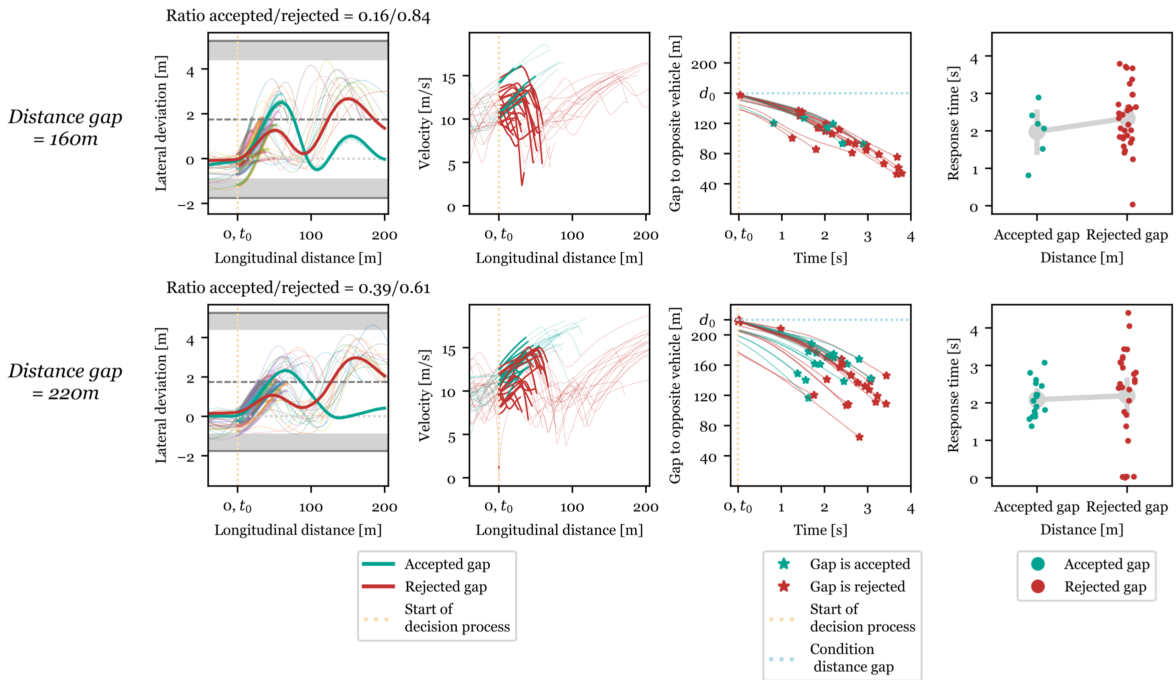

Figure C.21: Overview of data of participant 858.

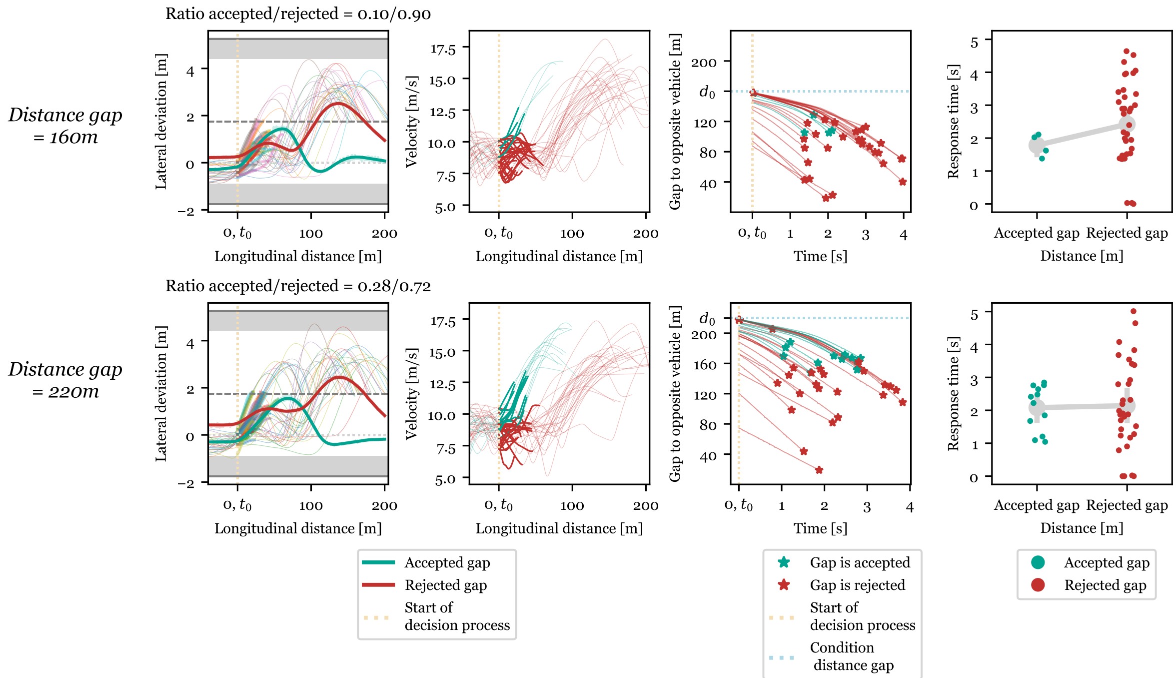

Figure C.22: Overview of data of participant 890.

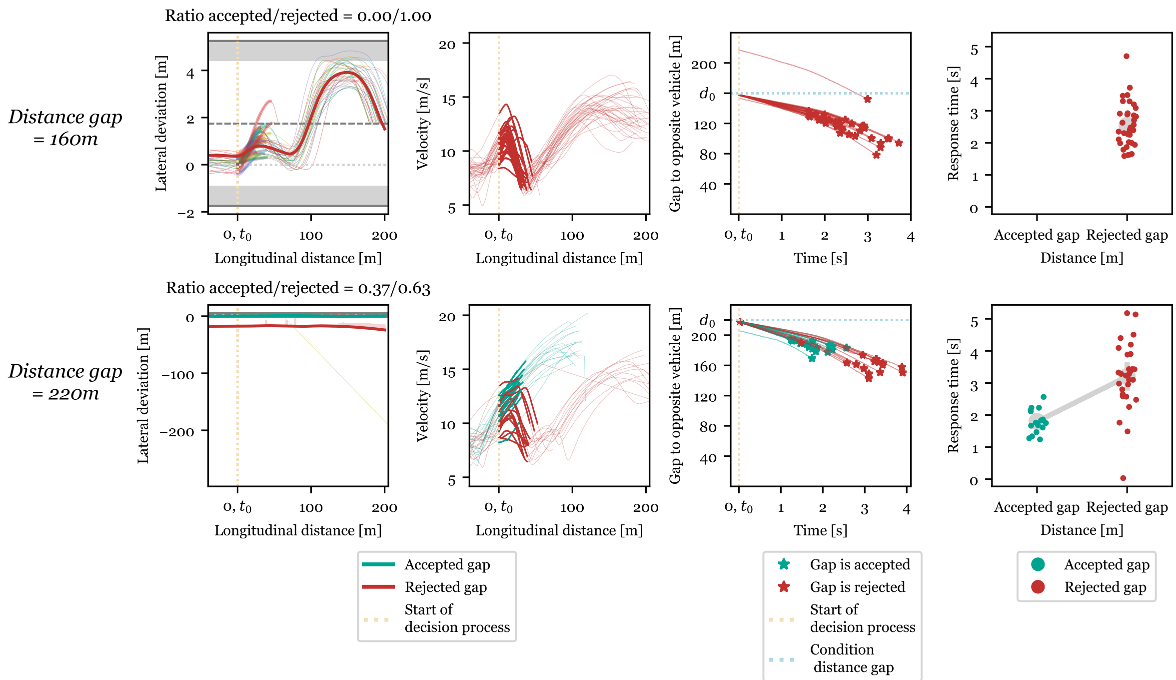

Figure C.23: Overview of data of participant 913.

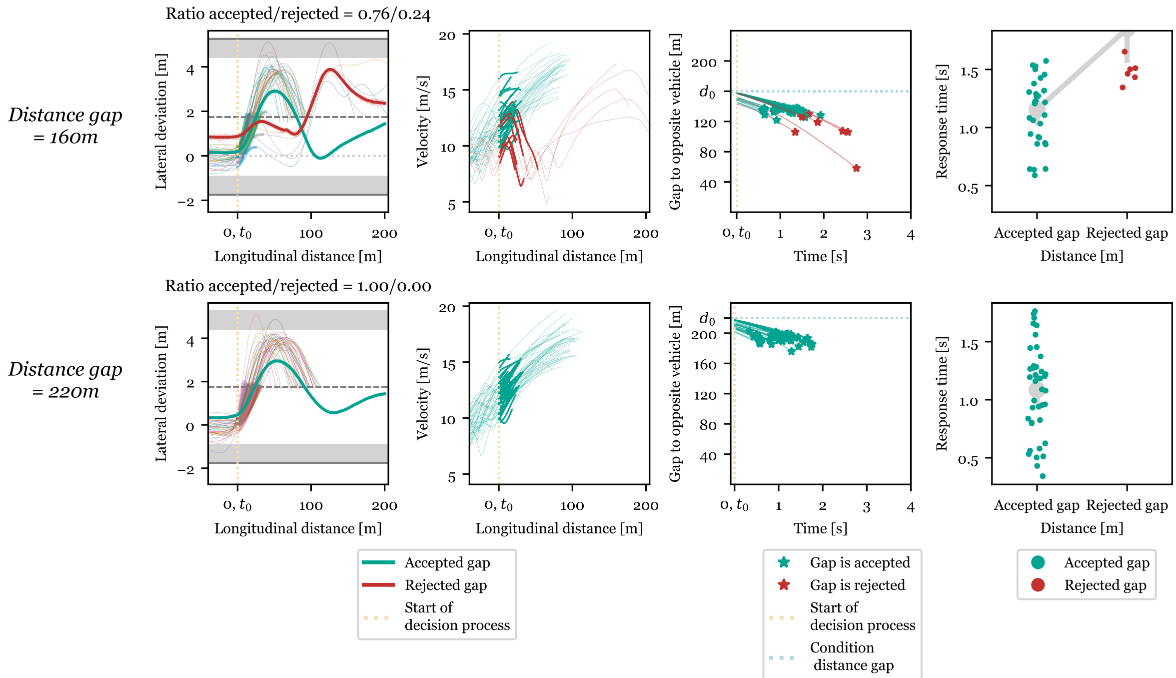

Figure C.24: Overview of data of participant 974.

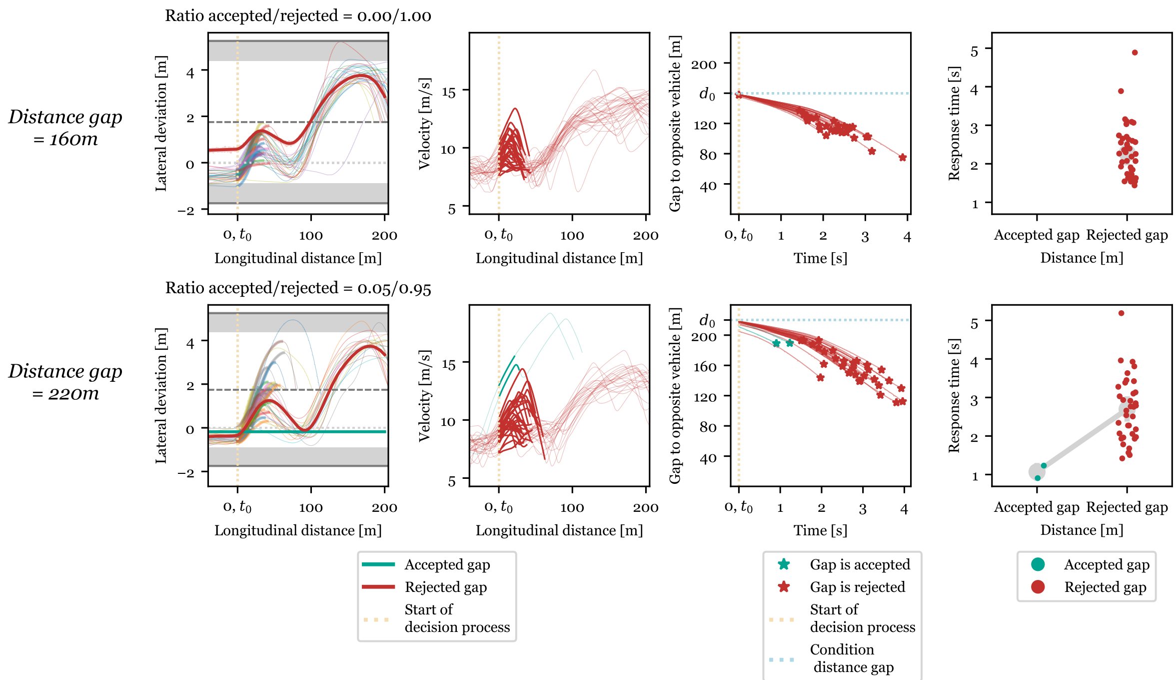

Figure C.25: Overview of data of participant 200.

D Complications in the experimental design

The original experimental design was to vary the time to arrival (TTA) and distance gap. This was done by changing the velocity of the oncoming vehicle. The velocity of the ego vehicle would be measured when it passed the last platoon vehicle. The velocity of the oncoming vehicle would then be adapted to get the desired TTA condition and be spawned with this velocity. However, after the oncoming vehicle was spawned, it took the controller of the vehicle in JOAN around 1.2s to gain the desired velocity and the participant would see the oncoming vehicle already before this. Figure D.1 shows the velocity profile of the oncoming vehicle for all trials. The delay can clearly be seen. Figure D.2 shows the distribution of start times of the decision processes and the end times of the decision processes. When the participant could see the oncoming vehicle, the oncoming vehicle would almost be standing still. Then, depending on the length of the response time, the oncoming vehicle would have gained a certain acceleration during the decision process. Due to the individual response times, this was different each trial. So, in short, the oncoming vehicle did not have the correct velocity at the start of the overtaking decision and the TTA values were not at the two designed condition values.

The distance gap was controlled at the start of the overtaking scenario, so to study the influence of TTA it also had to be measured at the start of the overtaking scenario. Because the velocity of the oncoming vehicle at the start of the overtaking situation was zero, the participants' velocity controlled the TTA (see Equation D.1). Because of this, I decided to neglect the velocity of the oncoming vehicle when calculating the TTA. Now the TTA was calculated using the distance condition and the participants' velocity at the start of the overtaking situation. Because the distance condition was a controlled independent variable, it was decided to neglect the TTA and focus on the participants' velocity.

However, as discussed before, for longer response times the oncoming vehicle would have a certain velocity at the end of the decision process. Figure D.3 shows the change of the velocity of the oncoming vehicle during the decision process. It can be seen that for a longer response time, the velocity change is also higher. So there are differences in the experimental situations that the participants perceived each trial. It is possible that the movement of the oncoming vehicle had some influence on the decision process and response time, that is now not accounted for in the data analysis. The experiment should be repeated with controlled TTA conditions, to study if there were any effects that were overlooked in the current analysis.

$$\text{TTA}_{\text{gap}} = \frac{\text{Distance}_{\text{gap}}}{v_{\text{oncoming}} + v_{\text{ego}}} \tag{D.1}$$

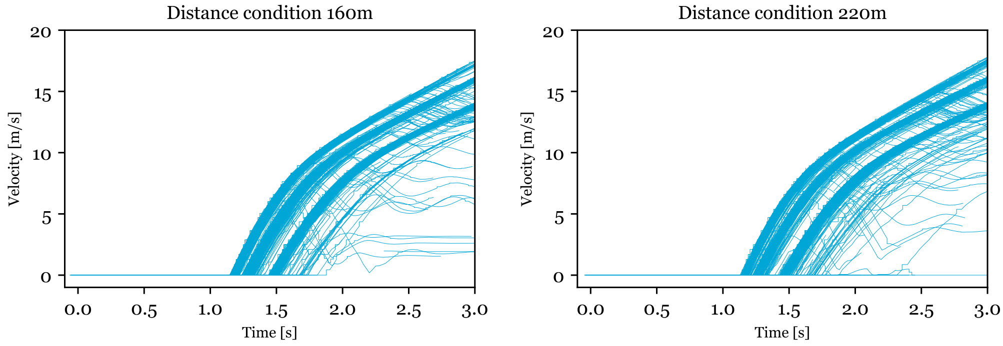

Figure D.1: Velocity of the oncoming vehicle. T=0 is the start of the overtaking situation.

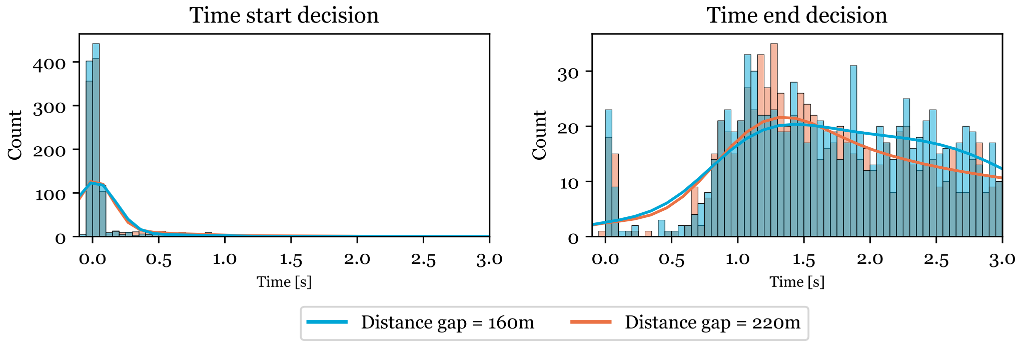

Figure D.2: Distribution of the start and end moments of the decision process. T=0 is the start of the overtaking situation.

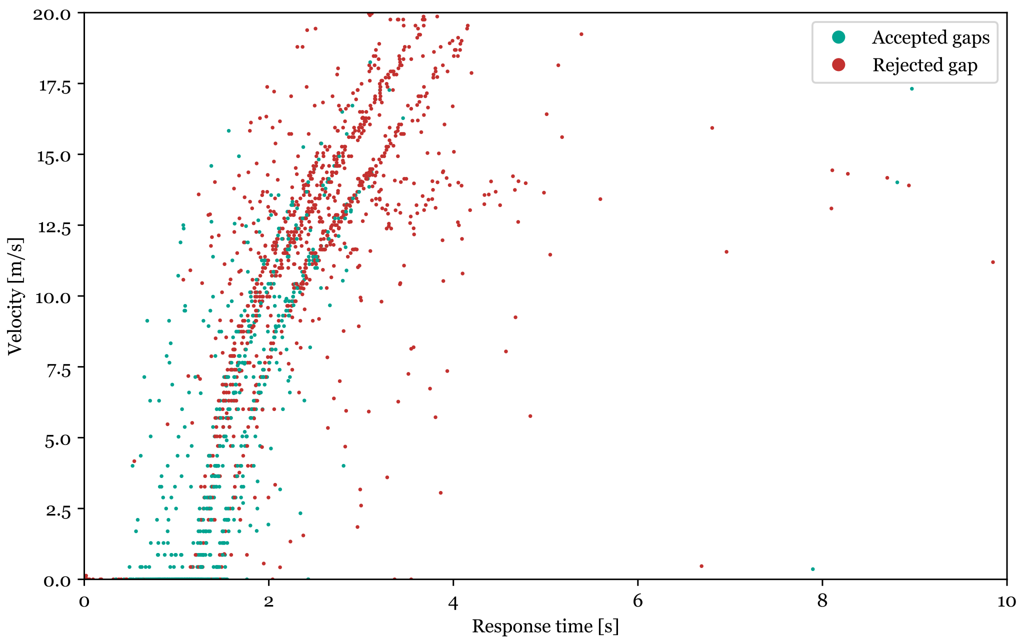

Figure D.3: The change of the velocity of the oncoming vehicle during the decision process.

E

Algorithm for measuring the response time

This appendix presents the used algorithm to calculate the response time. Furthermore, some screenshots of the simulation are included, to visualize the start and end of the decision process.

E.1. The algorithm for measuring the response time

The algorithm consists of three steps. First, the start of the decision process is calculated. Then, the decision outcome is determined. Then, based on the decision outcome, the end of the decision can be calculated.

Algorithm 1: Algorithm for measuring the response time

Data: `position_ego`, `position_oncoming`, `position_lastplatoon`, `position_lead`, `y_lanedivider`
Result: Decision, Response time

if `position_ego[longitudinal]` $>$ `position_lastplatoon[longitudinal]` **and** angle between the `position_oncoming` and `position_ego` $>$ angle between the `position_lead` and `position_oncoming`
    $t_{startdecision}$ = time when **if** statement is True
end
if `position_ego[longitudinal]` at $t_{startovertake}$ $<$ `position_oncoming[longitudinal]` at $t_{startovertake}$
    Decision = Accepted gap
    if `position_ego[lateral]` $>$ `y_lanedivider` **and** `position_ego[longitudinal]` $>$ `position_lastplatoon[longitudinal]`
        $t_{startovertake}$ = time when **if** statement is True
        $t_{enddecision} = t_{startovertake}$
    end
else if `position_ego[longitudinal]` at $t_{overtake}$ $>$ `position_oncoming[longitudinal]` at $t_{startovertake}$
    Decision = Rejected gap
    find peak of lateral `position_ego` after $t_{startdecision}$
    $t_{enddecision}$ = time when the lateral `position_ego` is at this peak
end
Response Time = $t_{enddecision}$ - $t_{startdecision}$

E.2. Visualizations of the response time

The following figures show screenshots in top view and participants' view of key moments in the experiment for the measurement of the response time.
As described in the experimental method in Section 3 in the paper, the oncoming vehicle is spawned when the last vehicle of the platoon passes the ego vehicle. Figure E.1 and Figure E.2 show the simulation before the oncoming vehicle is spawned.

Figure E.1: A screenshot of the top view of the experiment simulation, before the start of the overtaking situation. The last vehicle of the platoon has not yet passed the ego vehicle, so the oncoming vehicle is not spawned yet. The blue square shows the ego vehicle, the green square shows the last vehicle of the platoon and the yellow square shows the lead vehicle.

Figure E.2: A screenshot of the participants' view of the simulation before the last vehicle of the platoon has passed the ego vehicle. The yellow vehicle on the left is the last vehicle of the platoon and the lead vehicle is driving in front of the ego vehicle.

When the last platoon vehicle passes the ego vehicle, the oncoming vehicle is spawned, which can be seen in Figure E.3 and Figure E.5. When the oncoming vehicle is spawned, the overtaking situation has started.

Figure E.3: A screenshot of the top view of the experiment simulation, at the start of the overtaking situation. The last vehicle of the platoon has just passed the ego vehicle, so the oncoming vehicle is spawned. The blue square shows the ego vehicle, the green square shows the last vehicle of the platoon, the yellow square shows the lead vehicle and the red square shows the oncoming vehicle.

As described in the method for measuring the response time in Section 2 in the paper, the decision process starts when the driver can *see* the oncoming vehicle. Because of the width and the lateral position of the lead vehicle, the ego vehicle has to swerve to the left to properly see the oncoming vehicle and the available gap. This behavior can be seen in Figure E.4 and Figure E.5 shows what this looked like for the participant.

Figure E.4: A screenshot of the top view of the experiment simulation. The ego vehicle has swerved to the left, to be able to see the oncoming vehicle. The blue square shows the ego vehicle, the green square shows the last vehicle of the platoon, the yellow square shows the lead vehicle and the red square shows the oncoming vehicle.

Figure E.5: A screenshot of the participants' view of the simulation at the moment the last vehicle of the platoon passes the ego vehicle. The oncoming vehicle is spawned and the driver can *see* the oncoming vehicle and thus the available gap. The yellow vehicle on the left is the last vehicle of the platoon and the lead vehicle is driving in front of the ego vehicle.

After the start of the decision is defined, the outcome of the decision must first be determined. In Figure E.6 the ego vehicle crosses the lanedivider. As described in the method for measuring response time, this is the end of the decision process for accepted gaps, but not for rejected gaps. If the ego vehicle overtakes the lead vehicle before the oncoming vehicle, as shown in Figure E.7, the gap is accepted and the moment the ego vehicle crosses the lanedivider is the end of the decision process. The gap is rejected if the ego vehicle overtakes after the oncoming vehicle. Then, the moment the ego vehicle returns to the original lane before overtaking the lead vehicle is the end of the decision process, as shown in Figure E.8.

Figure E.6: A screenshot of the top view of the experiment simulation. The ego vehicle crosses the lane divider. The blue square shows the ego vehicle, the green square shows the last vehicle of the platoon, the yellow square shows the lead vehicle and the red square shows the oncoming vehicle.

Figure E.7: A screenshot of the top view of the experiment simulation. The ego vehicle overtakes the lead vehicle in front of the oncoming vehicle, so the gap is accepted. The blue square shows the ego vehicle, the green square shows the last vehicle of the platoon, the yellow square shows the lead vehicle and the red square shows the oncoming vehicle.

Figure E.8: After crossing the lanedivider the ego vehicle returns to the right lane and does not overtake the lead vehicle. The gap is rejected. The blue square shows the ego vehicle, the green square shows the last vehicle of the platoon, the yellow square shows the lead vehicle and the red square shows the oncoming vehicle.

F Random effects of the regression models

This appendix contains the individual intercepts for the three regression models that were calculated during in the statistical analysis.

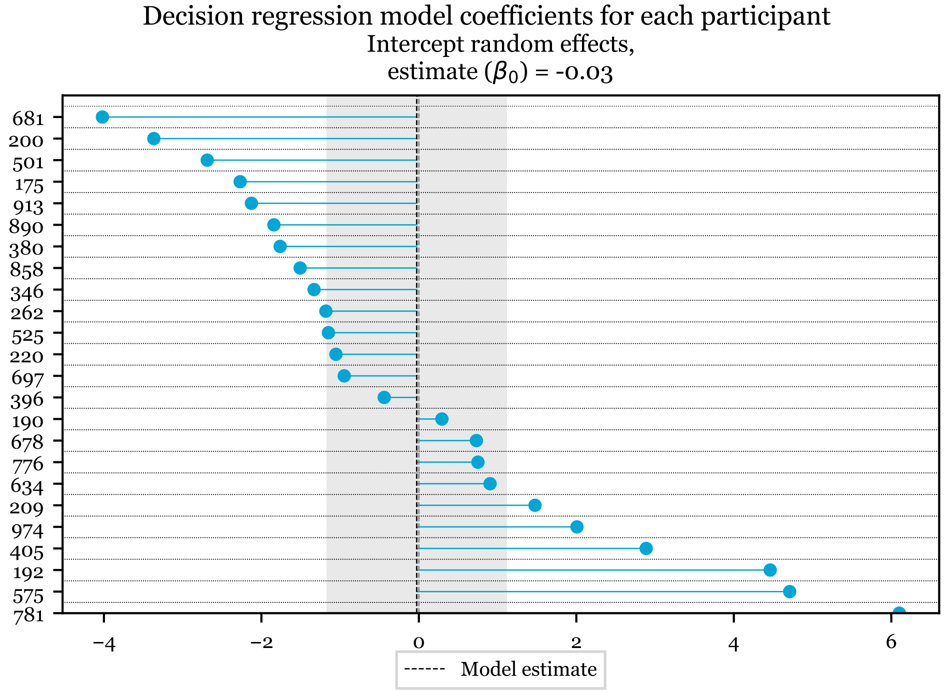

Figure F.1: Random effects of the logistic regression model for the decision outcome.

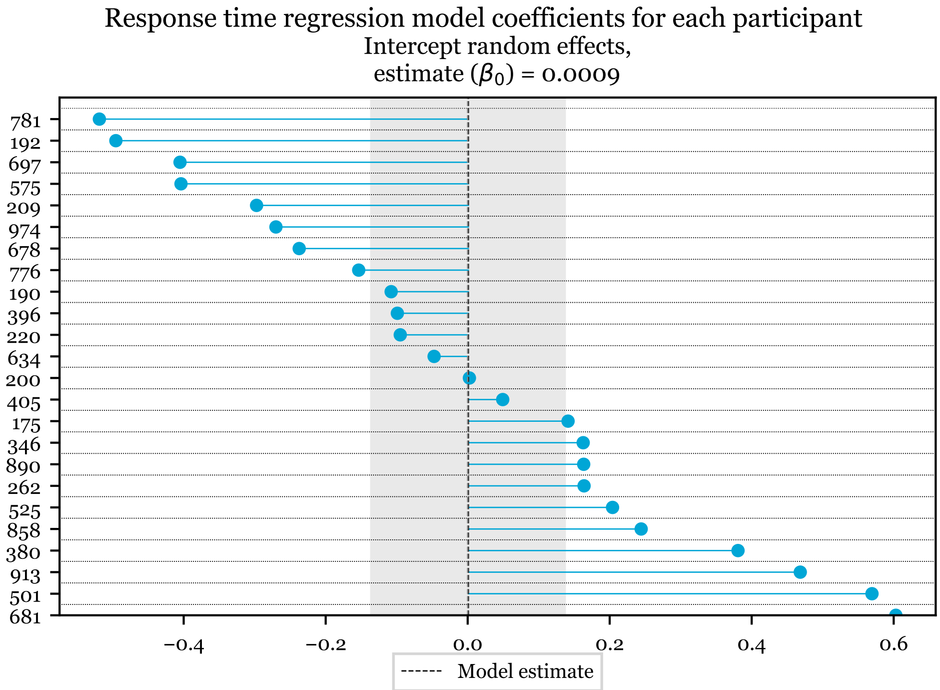

Figure F.2: Random effects of the linear regression model for the response time.

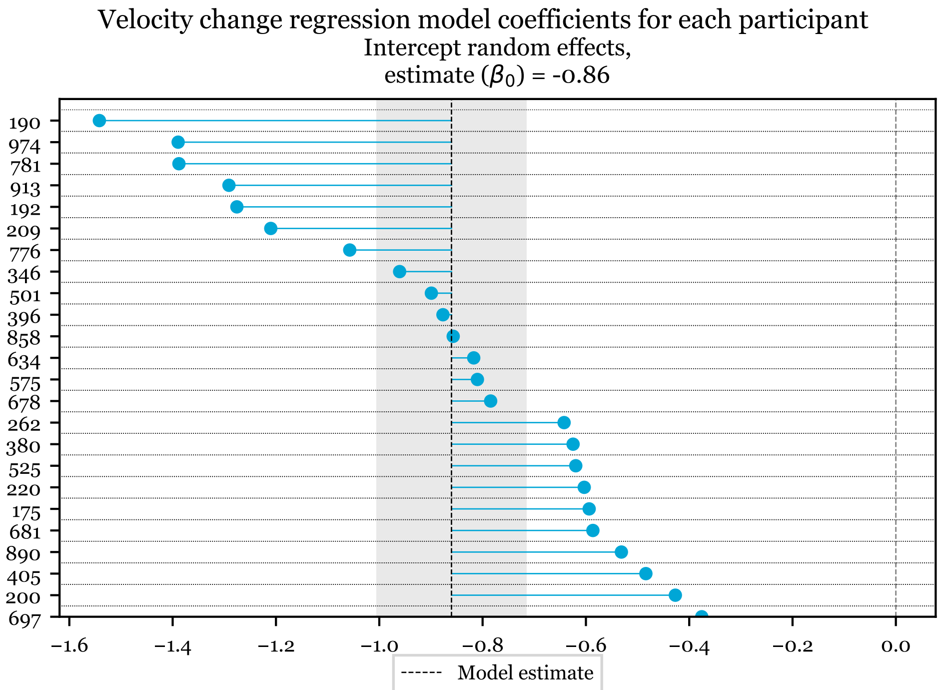

Figure F.3: Random effects of the linear regression model for the velocity change.

References

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