Inter- and intra-driver variability in lane change behaviour

A driving simulator study

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Master of Science Thesis

Delft University of Technology

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MASTER OF SCIENCE THESIS

For the degree of Master of Science in Mechanical Engineering at Delft University of Technology

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August 12, 2019

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The work in this thesis was supported by Cruden BV. Their cooperation is hereby gratefully acknowledged.

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Preface

This thesis "Inter- and intra-driver variability in lane change behaviour", is submitted for the degree of Master of Science at Delft University of Technology. It has been written to obtain the Master of Science degree in Mechanical Engineering under the supervision of prof.dr.ir D.A. Abbink and dr.ir S.M. Petermeijer at Delft University of Technology and ir. J. van Doornik at Cruden BV.

I would like to thank everyone who contributed to this research project, in particular my supervisors for their excellent support and guidance during this process. I also wish to thank all of my participants, without whose contribution this project would not have been possible.

To my colleagues at Cruden: I would like to thank you for your cooperation as well. It was always helpful to have a fresh perspective on the subject. I also benefitted from discussing and not discussing issues with friends and family. If I ever needed a distraction, you were there.

Christiaan Koppel

August 2019

“The one thing that unites all human beings, regardless of age, gender, religion, economic status, or ethnic background, is that, deep down inside, we all believe that we are above-average drivers.”

— *Dave Barry*

Chapter 1

Paper

Inter- and intra-driver variability in lane change behaviour

Christiaan N. Koppel

***Abstract*—Lane change manoeuvres are known to vary widely in lane change duration. This is thought to be an effect of the surrounding vehicles and personal preference of drivers. However, little is known about the effect on steering behaviour during a lane change manoeuvre. Moreover, the relation of the effect of traffic to inter- and intra-driver variability is unknown. This study focuses on quantifying inter- and intra-driver variability in lane change duration and steering behaviour during lane changes in two different traffic scenarios. In an exploratory study, 21 participants drove 30 lane change manoeuvres in a 6 DoF moving base driving simulator. Two scenarios were used: a closing gap in the target lane and a constant gap in the target lane, with 15 repetitions per scenario. The results show high inter-driver and intra-driver variability, for both lane change duration (M=6.34 s SD-inter=0.90 s SD-intra=1.26 s) and steering behaviour (e.g. maximum steering wheel angle M=4.14 deg SD-inter=1.62 deg SD-intra=1.34 deg). The effect of the scenario was not significant for lane change duration and maximum steering wheel angles. Additionally, it was shown that lane change duration only has a medium correlation with the maximum steering wheel angle (Pearson R(585)=-.48, p<0.001). Furthermore, the mean and variability of the lane change duration decreased when lane changes were initiated with a shorter distance to the slow lead vehicle. Concluding, the lane change duration does not fully determine steering behaviour during a lane change, making it an unsuitable metric for determining human-like lane change trajectories. It is therefore proposed to create trajectories based on steering behaviour. It seems that drivers exhibit high variability in lane change behaviour when spatio-temporal criticality with respect to traffic is low. Higher spatio-temporal criticality limits the mean and variability of the lane change duration. Future work should determine whether this variability is the result of driver preference or indifference. Additionally, future work should implement and test human-like lane change trajectories based on steering behaviour as opposed to lane change duration.**

***Index Terms*—lane change manoeuvre, driving simulator, driving behaviour, human-like trajectories**

I. INTRODUCTION

DRIVING tasks are transferred from human to machine at an ever-increasing pace. These systems take over, or assist, tasks previously performed by drivers, as illustrated by lane keeping assistance and adaptive cruise control. The focus of these systems is reducing workload and increasing comfort of drivers in addition to increasing safety. Consequently, the need for an understanding of human driving behaviour arises, as highly automated vehicles are made to exhibit human-like driving behaviour in order to increase trust of drivers [1], [2]. In lane change manoeuvres only the end goal, reaching the target lane, is known, which provides drivers with the opportunity to execute the lane change according to personal preference. Furthermore, lane change manoeuvres are known to vary widely in terms of lane change duration [3], [4].

The lane change manouevre is predominantly performed for overtaking slower lead vehicles in order to maintain a certain speed [5]. The manoeuvre can be divided into four parts. Firstly, an incentive to change lanes is required, for example a slow vehicle in front. This incentive results in the intention of the driver to change lanes. Thirdly, an appropriate and safe gap in the target lane has to be identified to merge into. Laslty, after this decision-making process, the lane change manoeuvre is executed.

Research on the topic of driver behaviour and modelling during lane changes has focused mostly on gap acceptance [6], [7] and lane change intent prediction [8]–[10] of drivers using the traffic situation, vehicle states and driver gaze measurements. However, less is known about the execution phase of the lane change. Research into the influences on the execution phase of the lane change has mostly been limited to the effects on the lane change duration for use in microscopic traffic flow simulation [3], [4], [11] or the effect of lane changes on traffic flow [12]. However, the effect of traffic on the lane change duration does not take into account variability between and within drivers. Furthermore, the lane change duration might not be suitable to characterize human lane change behaviour on its own.

Some studies did take into account human driving behaviour for creating lane change trajectories. Yao [13] uses the k-nearest neighbours (k-NN) algorithm to predict the end point of the lane change, by interpolating previous lane change durations based on the traffic situation at the start of the lane change. Butakov [14] used the traffic situation at the start of the lane change to predict the lane change duration based on personal previous lane changes in similar situations. Van Weperen [15] used the relative lateral position to the slower lead vehicle during previous manoeuvres to create a reference path. This reference path was then used in combination with a bicycle model to optimize a cost function in order to obtain the personalised human-like trajectory driven by the bicycle model. Tsoi [16] created an adaptive guidance system which generates a guidance trajectory based on the lane change duration, which is predicted by the initial lateral velocity of the lane change. A different, adaptable approach is proposed by Cramer [17]. In this approach, the lane change trajectory is adapted based on the driver input on the steering wheel during the lane change manoeuvre itself. This means the trajectory is continuously adapted to fit the wide range of human lane change behaviour.

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Fig. 1. The Cruden 6 degrees of freedom (6DoF) motion base driving simulator as used in the experiment, with actuated steering wheel, 210 degrees projection with side- and rear-view mirrors mounted to the a-pillars and windscreen frame.

So far, three methods for adapting the trajectory to fit the current needs of the driver have been seen: creating traffic adaptive trajectories, creating personalised trajectories or creating trajectories based on input of drivers. However, substantial evidence supporting one method over the other is not found. In literature, the range of lane change durations demonstrated by drivers is assumed to be a result of two factors: The traffic situation and the personal preference of the driver (inter-driver variability) [3], [18]. A third important factor, intra-driver variability, is mostly neglected.

Due to the use of traffic camera's, natural lane change behaviour of over 1200 vehicles is recorded and related to the traffic situation by Toledo [3]. The variation in lane change duration (M=4.6 s, Min=1.0 s, Max=13.3 s) is for 20% accounted for by the traffic situation. However, the lack of repetitions per driver makes it impossible to determine the effect of inter- and intra-driver variability. Butakov [14] found that the personal lane change prediction algorithm of one driver used on data from another driver increases errors above the baseline error, implying a difference between drivers, however no quantitative analysis was done. Both Butakov [14] and Yao [13] used on-road driving data, which results in natural driving behaviour, but lacks the reproducibility needed in order to quantify inter- and intra-driver variability. The relation between the effect of traffic and inter- and intra-driver variability is needed in order to make a substantiated decision on which adaptive approach is the most effective in terms of mitigating variability.

Additionally, most trajectory construction methods use the lane change duration to characterize the lane change trajectory. The duration is used to determine the start and end point of the lane change. Then, a standard kinematic or optimized trajectory is created between these points that satisfy some safety constraints and minimize for example the maximum jerk or the total kinetic energy [19]. This assumes that the lane change duration captures both the steering behaviour and the trajectory of the lane change, which has not been proven in literature. Additionally, research into the effect of traffic on steering behaviour and the related inter- and intra-driver variability is not found. Therefore, these trajectories, although safe, might not be in accordance with human driving behaviour, in terms of steering behaviour, which could lead to conflicts between driver and automation and eventually disuse of the system [20]. Furthermore, no clear definition of the lane change duration is present in literature [3], [21]–[23].

Therefore, an exploratory driving simulator study is done in which the aim is to answer the following questions. What is the effect of the traffic situation on lane change behaviour, in terms of lane change duration and steering behaviour? And, how does this effect relate to the inter- and intra-driver variability in lane change behaviour? Furthermore, does the lane change duration correlate with the steering behaviour during the lane change?

The remainder of this paper is organized as follows: section 2 introduces the method and experiment set-up. Section 3 presents the results of the experiment. Sections 4 and 5 discuss the results and summarize the conclusions respectively.

II. METHOD

Apparatus

The driving experiment was conducted on a six degrees of freedom (6-DoF) motion base simulator by Cruden, similar to the ones used in earlier research [24]. Sway motion cueing was based on the lateral position, scaled with respect to the width of the three-lane highway with a scaling factor of 0.125. The yaw motion was scaled equally and based on the vehicle heading [25]. The simulator consists of a moving hexapod and actuated steering wheel providing vestibular and haptic feedback. The visual environment was projected on a 210-degree projection screen using three projectors running at 120 Hz as seen in figure 1. Furthermore, the cockpit consisted of a driver seat, steering wheel with turn indicator, brake and accelerator pedals. Additionally, three screens were used as

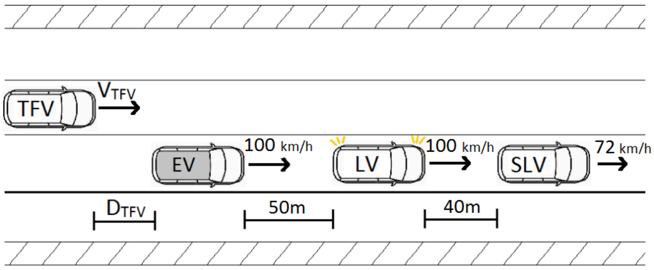

Fig. 2. Generic scenario visualisation. At the start of the lane change of the LV. This is the time that D_{TFV} is measured.

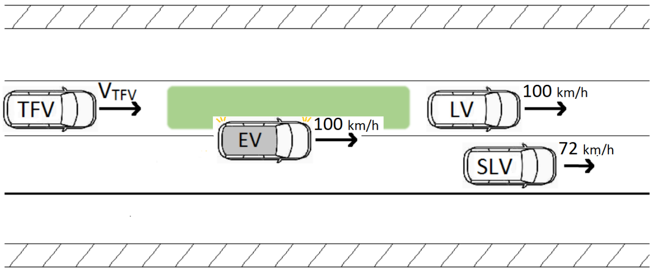

Fig. 3. Generic scenario visualisation. During the lane change of the EV, at the time of lane crossing.

rear-view mirrors, mounted to the windscreen frame and A-pillars. The force feedback on the steering wheel was provided by a control loader, with a maximum torque of 30 Nm, connected to a dedicated computer running at 1000 Hz. The Cruden Panthera internal car model was updated at 60 Hz and data was logged at 120 Hz. The integration of traffic into the simulation was done using VIRES virtual test drive software utilising the openDRIVE format.

Participants

A group of 22 participants (17 male, 5 female) participated in the experiment. The participants were recruited from within and outside of the Cruden office, of which 17 had prior experience with the driving simulator. The participants had a mean age of 28 years (SD 7.6 years). All participants had normal or corrected to normal vision and were in possession of a valid driver license. Participation was on a voluntary basis and no compensation was offered. One participant could not finish the experiment due to motion sickness, resulting in data for 21 (17 male, 4 female) participants.

Experiment design

The experiment was a within-subject design study in which the traffic situation was the within-subject factor. The participants completed three driving sessions, each driving session consisted of 10 lane change events in random order. The order of the driving sessions was counterbalanced according to the 3x3 Latin square in order to minimize order effects. Participants drove a total of 30 lane changes, 15 per lane change scenario from table I. The participants each drove a 4-minute practice session before the experiment on the three-lane endless highway in which they were urged to practice 10 overtaking manoeuvres. This was done in order to familiarize the participants with the driving simulator and the dynamics of the simulated vehicle during lane changes.

Scenarios: The driving experiment took place on a straight three-lane endless highway. Each participant drove three sessions of 7 minutes each. Two different overtaking scenarios were used during the experiment, resulting in 15 repetitions per participant per scenario. In the scenario, four cars were of importance. The ego vehicle (EV), the lead vehicle (LV), the slow lead vehicle (SLV) and the target following vehicle (TFV). The EV was driven by the participant with a fixed speed of 100 km/h. The LV was driving in front of the EV at a distance of 50m, roughly 2 seconds time headway (THW), with a fixed speed of 100 km/h, see figure 2. The SLV, driving at 72 km/h was the vehicle that both the LV and the EV had to overtake to maintain a speed of 100 km/h. The TFV is the car in the target lane that limits the size of the available gap in the target lane. Other cars were present in the leftmost lane and behind the EV, there was no interaction between these cars and the EV.

The LV started a lane change manoeuvre, with a duration of 6 seconds, to overtake the SLV when the distance between LV and SLV was 40m. From this moment, the EV was able to see the SLV and prepare for a lane change manouevre. Two different scenarios were created by varying the velocity of the TFV (V_{TFV})). The TFV is driving at a distance of 45m behind the EV in the target lane with a speed of 100 km/h. In the first scenario ($LC_{ClosingGap}$) the TFV accelerates to 105 km/h, closing the gap to the EV. In the second scenario ($LC_{ConstantGap}$) the TFV maintains a velocity of 100 km/h I, keeping the gap constant. This consequently results in a difference in distance between EV and TFV (D_{TFV}) at the start of the lane change of the LV (see table I). D_{TFV} is measured at the start of the lane change of the LV, as can be seen in fig 2.

To keep participants alert and motivated, each of the three driving sessions contained one unexpected event. Two of the three unexpected events were characterized by a suddenly braking SLV, after which the LV made a quick lane change to avoid the SLV. The SLV would then change lanes into the emergency lane just in time to avoid the EV. The third event was characterized by a TFV driving at 112 km/h, blocking the target lane for the EV long enough so that the EV had to make a quick lane change after being overtaken by the TFV. These three events were not used in data collection.

TABLE I
LANE CHANGE SCENARIOS (LC) WITH CORRESPONDING TIME TO COLLISION (TTC) AND TIME HEADWAY (THW) BETWEEN TFV AND EV. MEASURED AT THE START OF THE LANE CHANGE OF THE LV.

Scenario	V_{TFV} [km/h]	D_{TFV} [m]	TTC [s]	THW [s]
$LC_{ClosingGap}$	105	40	28.8	1.37
$LC_{ConstantGap}$	100	45	inf	1.62

Instructions

Participants were instructed to keep in the right lane of the three-lane highway and to change lanes when they needed to overtake slower vehicles. Participants were instructed to use the turn signal when changing lanes and were urged not to cross lane boundaries unless a lane change was being performed.

Lane change analysis

During the driving session the following signals were recorded with a sampling rate of 120Hz:

y	lateral position [m]
θ	steering wheel angle [deg]
ψ	heading angle [deg]
D_{front}	longitudinal distance of EV to the car in front [m]
D_{TFV}	longitudinal distance of EV to TFV [m]

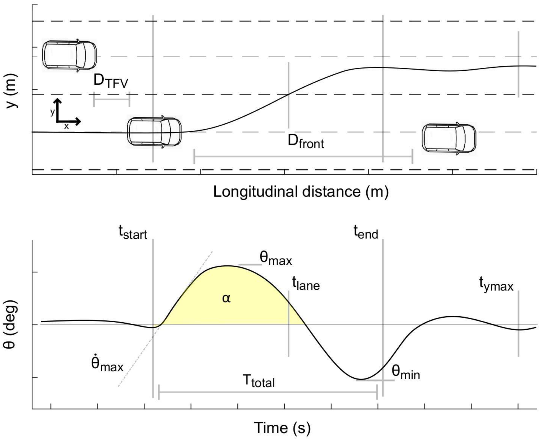

Fig. 4. Lane change trajectory with corresponding steering wheel angle and visualization of the lane change duration and steering characteristics.

The steering wheel angle θ was filtered with a fourth order low pass Butterworth filter with a cutoff frequency at 10Hz, the upper bound of the human control bandwidth [26], in order to eliminate noise. Lane changes to the left that followed shortly after a lane change to the right, essentially resulting in one steering manouevre, where not used in data analysis. More specifically, if the center of the EV was still in the center lane 10 seconds before the center of the EV crossed the lane from the right lane to the center lane, the lane change is not taken into account. This resulted in exclusion of 45 lane changes, 22 for $\mathrm{LC}_{\mathrm{ClosingGap}}$ and 23 for $\mathrm{LC}_{\mathrm{ConstantGap}}$, distributed over all participants. The following characteristics were determined for each lane change manoeuvre, see figure 4.

θ_{max}	Peak steering wheel angle [deg]. θ_{max} is the maximum positive value of the steering wheel angle during the lane change.
θ_{min}	Peak steering wheel angle [deg]. θ_{min} is the minimum value of the steering wheel angle during the lane change; the peak steering wheel angle to the right.
$\dot{\theta}_{max}$	Peak steering wheel rate [deg/s]. $\dot{\theta}_{max}$ is the maximum value of the steering wheel rate between t_{start} and the time of θ_{max}.
α	Integral of the steering wheel $\int_{t_{start}}^{t_{zc}} \theta$ [deg s]. The integral of θ during the first half of the lane change between t_{start} and the time that θ crosses zero t_{zc}. Could be seen as the amount of steering.
t_{start}	The start of the lane change [s]. t_{start} is defined as the last moment before the θ_{max} peak in which: $\theta < \frac{1}{2}\theta_{max}$ (1) and $\dot{\theta} < 0.1$ deg/s (2) and $y_{offset}(t_{start}) < 0.5$ m (3) With y_{offset} being the lateral distance to the lane center of the current lane.
t_{end}	The end of the lane change [s]. t_{end} is defined as the first moment after θ_{min} in which: $\psi < 0.1$ deg (4) and $y_{offset}(t_{end}) < 0.4 + 0.5 * y_{offset}(t_{ymax})$ (5) With y_{offset} being the lateral distance to the lane center of the current lane.
t_{lane}	The time of line crossing [s]. The point in time at which the center of gravity of the EV crosses the lane boundary during the lane change. This point in time is taken as $t = 0$ when analysing lane changes.
T_{total}	The total duration of the lane change [s]. Defined as the time between t_{start} and t_{end}.
T_{half}	The duration of the half lane change [s]. Defined as the time between t_{start} and t_{lane}.
T_{delay}	Time delay of the lane change [s]. Time delay with respect to the lane change of the LV. Defined as the time between the moment that LV has a lateral distance of more than 2 m to EV and the start of the lane change of the EV. Defining if the EV has a TTC to LV or to SLV at the time t_{start}
$D_{front}(t)$	Distance to the car in front (LV or SLV) at time t [m]. $D_{SLV}(t_{start})$ is the distance to the SLV at time t_{start}. $D_{LV}(t_{start})$ is the distance to the LV at time t_{start}.

III. RESULTS

Lane change duration

Figure 5 shows the kernel density estimate of the lane change duration in the $LC_{ClosingGap}$ scenario. This illustrates the distribution of the lane change duration per participant and the high inter- and intra-driver variability for the lane change duration. In figure 6 the mean lane change duration per participant is plotted for both lane change scenarios $\mathrm{LC}_{\mathrm{ClosingGap}}$ and $\mathrm{LC}_{\mathrm{ConstantGap}}$. The errorbars indicate the 95% prediction interval. As can be seen from figure 6, the effect

TABLE II

DESCRIPTIVE STATISTICS FOR BOTH LANE CHANGE SCENARIOS $LC_{ClosingGap}$ AND $LC_{ConstantGap}$ AND DEPENDENT SAMPLES T-TEST BETWEEN $LC_{ClosingGap}$ AND $LC_{ConstantGap}$. M= MEAN, SD= STANDARD DEVIATION BETWEEN PARTICIPANTS (INTER-DRIVER VARIABILITY), MEAN SD = THE MEAN OF THE STANDARD DEVIATION PER PARTICIPANT (INTRA-DRIVER VARIABILITY), T= T-STATISTIC, D.F.= DEGREES OF FREEDOM, P= P-VALUE, D= COHEN'S D

	$LC_{ClosingGap}$			$LC_{ConstantGap}$						
	M	SD	Mean SD	M	SD	Mean SD	t	d.f.	p	d
T_{half} [s]	3.04	0.48	0.57	3.06	0.45	0.58	-0.43	20	0.67	-0.094
T_{total} [s]	6.23	0.89	1.18	6.45	0.90	1.33	-1.60	20	0.14	0.35
θ_{max} [deg]	4.20	1.65	1.27	4.07	1.59	1.41	1.12	20	0.27	0.25
$-\theta_{min}$ [deg]	4.14	1.57	1.53	3.91	1.16	1.42	1.51	20	0.15	0.33
α [deg s]	6.64	1.24	1.24	6.37	1.20	1.37	2.44	20	0.024	0.53
$\dot{\theta}_{max}$ [deg/s]	15.2	4.78	6.20	15.3	6.08	6.78	-0.12	20	0.90	-0.027

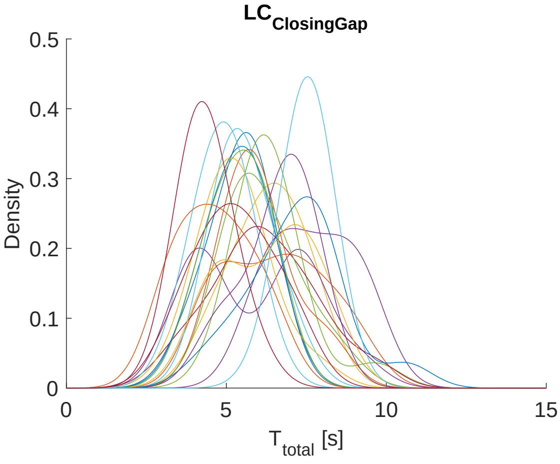

Fig. 5. Kernel density estimate of the lane change duration T_{total} with bandwidth 0.8 s. Shown per participant for $LC_{ClosingGap}$.

of the scenario is relatively low compared to the inter- and intra-driver variability. A paired samples t-test was conducted to compare the lane change duration T_{total} in $LC_{ClosingGap}$ and $LC_{ConstantGap}$. There was no significant difference in T_{total} for $LC_{ClosingGap}$ (M=6.23, SD=0.89) and $LC_{ConstantGap}$ (M=6.45, SD=0.90) conditions; t(20)=-1.60, p=0.14, d=0.35. Meaning that no statistically significant difference is found in lane change duration between the traffic scenarios. The same goes for the duration of the first half of the lane change (see table III).

Steering behaviour

In figure 7 the mean θ_{max} is plotted per participant for both scenarios. The 95% prediction intervals are indicated and show high variability within and between participants. As can be seen, no obvious main effects of the traffic scenario can be seen. A paired samples t-test was conducted to compare the θ_{max}, θ_{min}, α and $\dot{\theta}_{max}$ in $LC_{ClosingGap}$ and $LC_{ConstantGap}$. The results of the t-test are shown in table II. For θ_{max}, θ_{min}, and $\dot{\theta}_{max}$ no significant differences were found between the two scenarios. Only α shows a signifcant difference between the two scenarios.

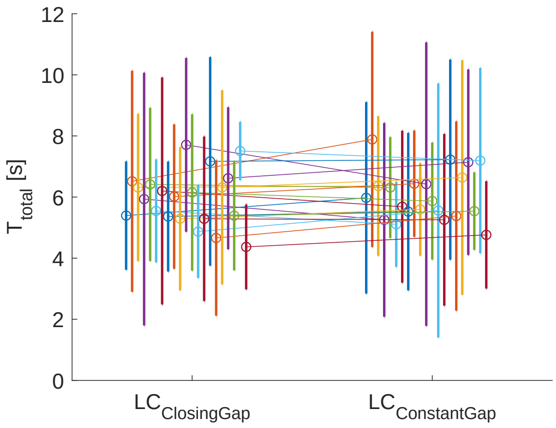

Fig. 6. Mean and 95% prediction interval of the population per participant for both scenarios for T_{total}. Means of participants of both scenarios are connected by lines. No significant effect of the scenario is found.

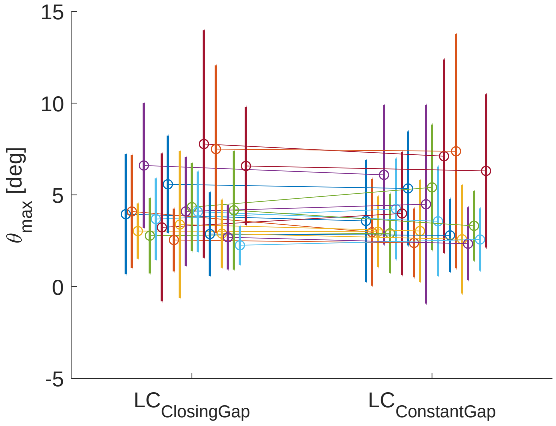

Fig. 7. Mean and 95% prediction interval of the population per participant for both scenarios for θ_{max}. Means of participants of both scenarios are connected by lines. No significant effect of the scenario is found.

From table II it can be seen that intra- and inter-driver variability is relatively high for all lane change characteristics compared to the effect of the traffic scenario.

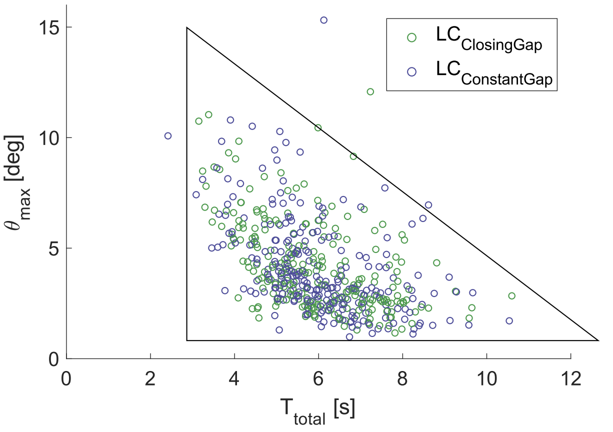

Fig. 8. Peak steering wheel angle θ_{max} versus lane change duration T_{total} for all participants per scenario. Correlation coefficient of R=-.48.

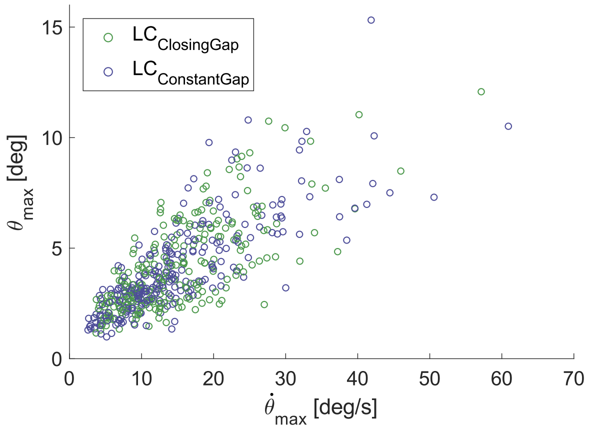

Fig. 9. Peak steering wheel angle θ_{max} versus peak steering wheel rate $\dot{\theta}_{max}$ for all participants per scenario. Correlation coefficient of R=.77.

Lane change duration versus steering behaviour

The results of the Pearson correlation indicated that there was a significant negative association between lane change duration T_{total} and peak steering wheel angle θ_{max} (R(585) =-.48, p<0.001). The correlations of the other steering behaviour metrics can be seen in table III. Looking at the first half of the lane change: the results of the Pearson correlation indicated that there was a significant negative association between lane change duration T_{half} and peak steering wheel angle θ_{max} (R(585) =-.61, p<0.001).

The Pearson correlation only indicates a medium correlation with T_{total}, which is supported by figure 8, from which can be seen that high T_{total} corresponds with low θ_{max}. Inversely, low θ_{max} does not necessarily correspond with high T_{total}. On the other hand, high θ_{max} indicates a low T_{total}, whereas again the inverse is not necessarily true. As an example: a T_{total} of 6 seconds could correspond with a θ_{max} between 1 and 10 deg. On the other hand, a θ_{max} of 2 deg could correspond with a T_{total} between 5 and 10 s.

Looking at figure 9 and table III it can be seen that a high correlation is found between θ_{max} and $\dot{\theta}_{max}$. The results of the Pearson correlation indicated a significant positive association of R=.77.

Spatial context and lane change initiation

Although the lane change scenario only shows a significant, but small, main effect for α, the timing of the manoeuvre influences the traffic situation at the start of the lane change. Therefore, only looking at the traffic scenario ignores some spatial context of the lane change manoeuvre.

Looking at figure 10 a clear difference between two groups can be seen. The first group of lane changes is initiated when the LV is still in front of the EV and therefore shows the distance to the LV on the x-axis. The second group of lane changes on the other hand is initiated after the LV is out of TTC range of the EV; the lateral distance of LV to EV is more than 2 m. Therefore, figure 10 shows the distance to the SLV on the x-axis for this group. Note that 85 lane change manoeuvres had missing data for T_{delay}, this was caused if the EV always stayed within 2 m laterally from the LV. Thus, the 85 missing lane changes would be below the 0 second line.

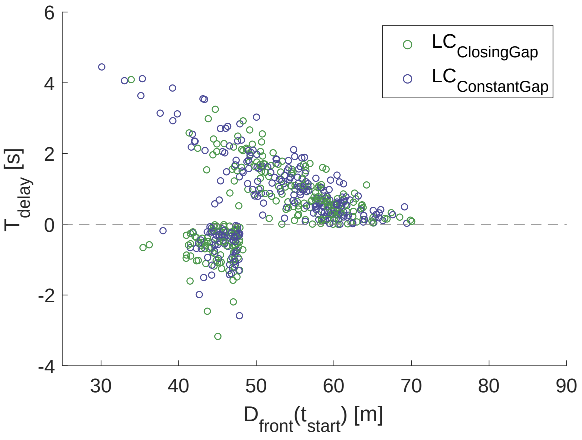

Fig. 10. Time delay T_{delay} plotted against the distance to the car in front at the start of the lane change $D_{front}(t_{start})$. The line at 0 seconds denotes the time that LV has a lateral distance of more than 2 m to the EV. D_{front} above the 0 second line correspond with distance to SLV, D_{front} below the 0 second line correspond with distance to LV. Note that 85 lane change manoeuvres had missing data for T_{delay}.

In figure 11, the distance to the SLV $D_{SLV}(t_{start})$ is pictured against T_{total}. Only the lane changes with T_{delay} bigger than 0 seconds are shown. Although only a weak correlation of R=.35 is found, it can be seen that the most variability in T_{total} is exhibited at longer distances to the SLV. For shorter distance to the SLV both the variability and mean of T_{total} become lower. Correlations to the other characteristics are shown in table III. For the steering behaviour the the trend of less variability at shorter distance to the SLV is not found. This is illustrated byt θ_{max} in figure 12.

In figure 13 the half lane change duration T_{half} is plotted against the distance to the SLV $D_{SLV}(t_{start})$. Only the lane changes with T_{delay} bigger than 0 seconds are shown. The same trend can be seen here, lower variability at shorter

TABLE III
Pearson correlation coefficients r shown below the diagonal, p-value corresponding to the correlation shown above the diagonal (n=585). (n=288) for correlations with $D_{SLV}(t_{start})$. For correlations with $D_{TFV}(t_{start})$ only $LC_{ClosingGap}$ is used (n=293)

	T_{half}	T_{total}	θ_{max}	$-\theta_{min}$	α	$\dot{\theta}_{max}$	$D_{SLV}(t_{start})$	$D_{TFV}(t_{start})$
T_{half}	-	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004
T_{total}	0.71	-	<0.001	<0.001	<0.001	<0.001	<0.001	0.046
θ_{max}	-0.61	-0.48	-	<0.001	<0.001	<0.001	<0.001	0.15
$-\theta_{min}$	-0.49	-0.52	0.66	-	<0.001	<0.001	<0.001	0.005
α	-0.37	-0.48	0.72	0.67	-	<0.001	0.024	0.90
$\dot{\theta}_{max}$	-0.47	-0.37	0.77	0.48	0.57	-	<0.001	0.014
$D_{SLV}(t_{start})$	0.34	0.35	-0.28	-0.30	-0.12	-0.21	-	0.016
$D_{TFV}(t_{start})$	0.17	0.12	-0.084	-0.16	0.0077	-0.14	0.19	-

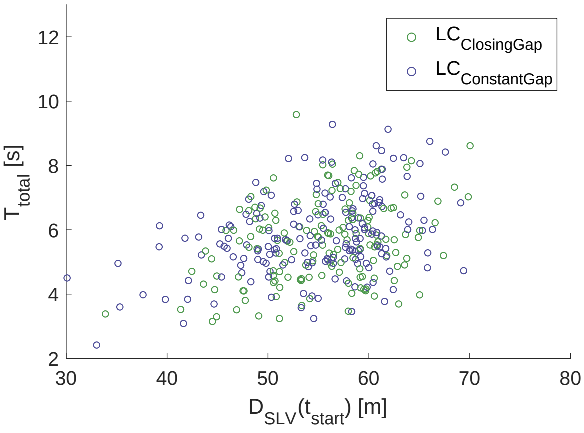

Fig. 11. Lane change duration T_{total} against the distance to the SLV D_{SLV} at time t_{start} for all participants, for $T_{delay} > 0s$. Correlation coefficient R= .35.

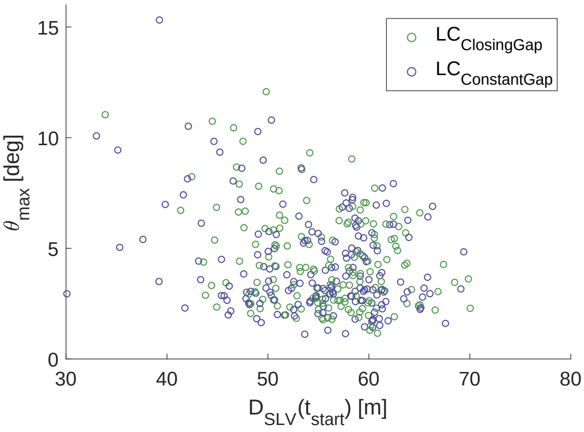

Fig. 12. θ_{max} against the distance to the SLV D_{SLV} at time t_{start} of EV for all participants, for $T_{delay} > 0s$. Correlation coefficient R=-.28

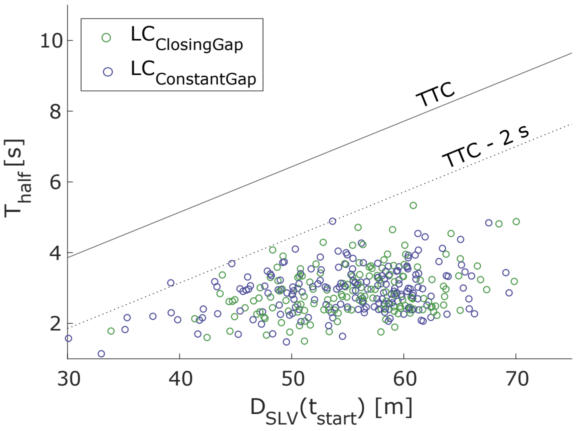

Fig. 13. First half of the lane change T_{half} against the distance to the SLV D_{SLV} at time t_{start} for all participants, for $T_{delay} > 0s$. The lines correspond with TTC and TTC -2 s. Correlation coefficient R= .34.

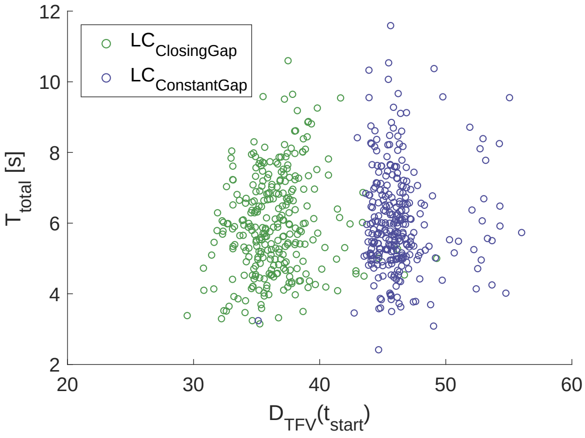

Fig. 14. Lane change duration T_{total} against the distance to the TFV D_{TFV} at time t_{start} for all participants. Correlation coefficient R=.17 for $LC_{ClosingGap}$.

distance to the SLV. Two lines are plotted indicating the TTC and the TTC -2 s at the corresponding distance to the SLV. It can be seen that the TTC -2 s line coincides with the slope of decreasing variability in T_{half}.

In figure 14, the distance to the TFV is plotted against T_{total}.

Only the lane changes with T_{delay} bigger than 0 seconds are shown. Although only a weak correlation is found (R=.17 in LC$_{\text{ClosingGap}}$ condition) it seems that there is a lower variability at shorter distances to TFV. For steering behaviour, the trend of less variability at shorter distance to the SLV is not found.

IV. DISCUSSION

Lane change behaviour

In addition to lane change duration, this study investigated steering behaviour of the participants in two different traffic scenarios. The aim of this study was answering the following questions. What is the effect of the traffic situation on lane change behaviour, in terms of lane change duration and steering behaviour? And, how does this effect relate to the inter- and intra-driver variability in lane change behaviour? Furthermore, does the lane change duration correlate with the steering behaviour during the lane change?

Literature often uses the lane change duration as metric to characterize a lane change, assuming that the variation in steering behaviour, and consequently in the trajectory, is accounted for by the variation in lane change duration. However, the variation in steering behaviour is not totally explained by the lane change duration. This is supported by the Pearson correlations for the steering metrics that can be seen in III of which the correlations between T_{total} and θ_{max}, θ_{min} and α are R=-.48, R=-.52 and R=-.48 respectively. These are only medium correlations and from these correlations it can be seen that variations in T_{total} only account for as much as 27% of the variation in θ_{max}, θ_{min} and α. Additionally, as can be seen from figure 8 a known lane change duration T_{total} could correspond with a wide range of steering wheel angles θ_{max}. The same goes for the other steering metrics. Therefore, it can be said that the lane change duration does not adequately explain variations in steering behaviour.

Furthermore, the lane change duration is not easily measured. This is especially true for determining the end point of the lane change, since the transition from lane changing to lane keeping is not evident. Additionally, literature uses a wide variety of methods for determining the start and ending of the lane change manouevre, complicating comparisons between studies [3]. For example: Salvucci [22] studied the time course of a lane change and let participants indicate verbally the intention to change lanes. Hetrick [21] indicated the start and end of the lane change manually by looking at the lateral position and steering wheel angle. According to van Winsum [23], the lane change starts when the steering action is initiated and no criterion for the end of the lane change is used. Not only does this complicate the comparison of the lane change duration, this also illustrates the difficulty in determining a consistent lane change duration. Taking into account that the lane change duration is hard to determine and does not capture the variations in steering behaviour, the lane change duration is no reliable metric in determining steering behaviour and creating lane change trajectories.

Spatial context - scenarios

What stands out by looking at the effect of the traffic scenario in table II is the lack of effect of the traffic scenario. In terms of lane change duration, no effect of the scenario was found. The lack of a significant effect has multiple reasons. The effect of surrounding traffic is relatively small and accounts only for 20% of the variation in lane change duration [3], this is supported by the finding of relatively high inter- and intra-subject variability. Furthermore, the timing of drivers to initiate the lane change affects the traffic scenario, more specifically it affects the distances to the SLV and the TFV which in turn affect the lane change duration. Looking at steering behaviour, a significant effect of the traffic scenario was found in terms of $alpha$, in which the mean α decreased from 6.60 ± 1.22 deg s to 6.33 ± 1.17 deg s. Although this effect is significant, in practice the inter- and intra-person variability are much larger, resulting in a negligible effect. It can thus be said that the scenario had no overall effect on lane change behaviour.

Spatial context - traffic

Slow lead vehicle: The timing of drivers in starting their lane change influences the traffic context during the lane change. Therefore, the effect of distances to relevant traffic participants (SLV and TFV) on lane change behaviour is assessed in addition to the effect of the scenarios. As can be seen from figure 11 and 13, a positive correlation is found between the lane change duration T_{total} and the distance to the SLV $D_{SLV}(t_{start})$ (r=.35), the same goes for T_{half} (R=.34). This is in accordance with literature, that found a decrease in lane change duration with decreasing spacing to the vehicle in front [3]. In addition to the correlation, a decrease in variability can be seen with decreasing distance to the SLV for both T_{total} and T_{lane}. Looking at figure 13, the variability seems to be reduced by safety margins of participants. The lane boundary was crossed before the TTC to the SLV was lower than 2 s. A 2 s safety margin seems to be the upper limit for the duration of the first half of the lane change. Meaning: the distance to the car in front is positively correlated with lane change duration and the lane change duration seems to show lower variability at shorter distances to the SLV.

For steering behaviour, as illustrated by θ_{max} in figure 12 the correlation is negative (R=-.28), meaning that longer distances to SLV result in lower peak steering wheel angles. This is expected, since T_{total} and θ_{max} are negatively correlated. Looking at variability however, a clear trend is not seen.

Target following vehicle: Looking at the distance to the TFV (figure 14), a clear distinction between the scenarios can be seen. Looking only at LC$_{\text{ClosingGap}}$, a correlation of R=.19 is found. In figure 14, it can be seen that the LC$_{\text{ClosingGap}}$ scenario shows a somewhat similar trend as figure 11; decreasing mean and variability for decreasing distance to TFV. However, the D_{TFV} and D_{SLV} are not independent for the LC$_{\text{ClosingGap}}$ scenario. Therefore, the influence of the D_{TFV} cannot be confirmed.

Spatio-temporal criticality: In terms of traffic context it seems that spatio-temporal criticality in the traffic situation influences the lane change duration and its variability, illustrated by the distance to the SLV in figure 11. Low spatio-temporal criticality results in high variability in lane change duration and vice versa. Thus, creating trajectories based on the traffic situation is most useful in situations with higher spatio-temporal criticality. It could however be argued that trajectories in more critical situations are governed by safety rather than comfort and would therefore benefit least from human-like lane change trajectories. Additionally, one could wonder if the high variability in lane change behaviour in low spatio-temporal criticality conditions is a matter of preference, or just a lack of urgency leading to satisficing behaviour of drivers [27], [28].

Human-like lane change trajectories

Taking into account the inability of the lane change duration to predict steering behaviour and the difficulty in creating robust criteria for the start- and endpoints of the lane change, it is argued that steering behaviour should be leading in creating human-like lane change trajectories. Moreover, steering behaviour is the input from the driver and results in the vestibular and visual feedback for the driver. It could therefore be argued that the lane change duration is a consequence of desired steering behaviour and not a goal on its own. Relating this to assistance systems, it is arguably more important that the manouevre feels right, in terms of vestibular and haptic feedback, than that it takes a certain amount of time.

Looking at the spatial context, the effect on the lane change duration in high spatio-temporal critically situations seems to be the effect of drivers maintaining a minimum safety margin 13. Therefore, the lane change duration could be used as a safety constraint when creating human-like lane change trajectories.

When the lane change duration is not considered as a goal on its own, but rather as the result of steering behaviour, the method for creating trajectories should change accordingly. Instead of creating a smooth trajectory which is constrained by the start- and endpoints of the lane change, a smooth trajectory should be created determined by the maximum steering wheel angles θ_{max} and θ_{min} for example. The maximum steering wheel angles are hypothesized to describe human lane change behaviour due to their relation to vestibular and haptic feedback during the lane change.

Traffic adaptive trajectories

Unfortunately, in terms of lane change behaviour no effect of the traffic scenario was found. However, other research did find an effect of the traffic situation on the lane change duration [3], [11] although only 20% of the variation in lane change duration was accounted for. More research should be done in determining the effect of the traffic situation on the steering behaviour during lane changes in order to create human-like trajectories based on the traffic situation. What can be concluded is that traffic adaptive trajectories alone will not be able to mitigate all variation in lane change trajectories due the relatively high inter- and intra-driver variability in both lane change duration and steering behaviour.

Personalised lane change trajectories

Personalized lane change trajectories have been proposed in order to accommodate the personal preference of drivers, mitigating inter-driver variability in lane change behaviour [14], [15]. However, due to the high intra-driver variability this strategy might only provide half of the solution. Looking at table II, it can be seen that the intra-driver variability (Mean SD) is in the same order of magnitude as the inter-driver variability (SD) for all lane change behaviour metrics. This means that drivers are as different from one another as they differ between consecutive lane change manouevres in the same traffic scenario. Personalised trajectories will therefore only mitigate inter-driver variability, neglecting the intra-driver variability. In order to mitigate intra-driver variability in addition to inter-driver variability, adaptable systems such as proposed by Cramer [17] could be integrated in lane change assistance systems. These systems let the driver adapt the trajectory during the manouevre to fit the driver's needs at that moment.

Input based trajectories

Input based trajectories can be very useful when no information on traffic or driver is available. Without any prior knowledge of the traffic situation or driver, an adaptive lane change trajectory can be created. For example, Tsoi [16] uses the initial lateral velocity as a predictor for the lane change duration. This lane change duration is then used to create a standard reference trajectory between the start- and endpoint of the lane change. Alternatively, the $\dot{\theta}_{max}$ could be used as a predictor for θ_{max}. As can be seen from table III, θ_{max} is highly correlated with $\dot{\theta}_{max}$ (Pearson R=.77), resulting in 59% variation accounted for. This is especially useful when creating input based lane change assistance systems that predict the trajectory, since $\dot{\theta}_{max}$ is the first metric to be measured at the start of the lane change. The maximum steering wheel angles can then be predicted and used for creating a smooth lane change trajectory. In addition to steering wheel angles, vehicle speed should be taken into account, since the steering wheel angle in lane changes is dependent on vehicle speed [23], [29].

limitations

The fixed speed of the ego vehicle did accommodate the possibility to create reproducible scenarios. However, this eliminated the possibility to accelerate during the lane change, excluding an integral part of lane changing behaviour. Additionally, this did not allow for the investigation of steering behaviour with different vehicle speeds. Furthermore, the other road users were pre-programmed, which removed the possibility of interaction or negotiation. Additionally, these pre-programmed road users made for the scenarios to be predictable to some extent. As can be seen from figure 10 a lot of lane changes are made well before the LV has left the lane, suggesting that participants started to follow the LV without due regard of the SLV.

This research only took into account two different traffic scenarios, which resulted in similar lane change behaviour for both scenarios. Research on realistic driving data did show an effect of the traffic situation on lane change duration. Although more contrasting scenarios might influence the lane change behaviour more, this research does quantify the inter- and intra-driver variability during these manouevres. Relating this to the effects of traffic found in [3], the effects of inter- and intra-driver variability are high compared to the effect of traffic.

The program that was used to create the traffic environment had some variability in distances and timing with respect to the preprogrammed scenarios. An example of this can be seen in figure 14, in which the $\mathrm{LC}_{\mathrm{ConstantGap}}$ condition shows variability in the $\mathrm{D}_{\mathrm{TFV}}$. This variability slightly alters the scenarios that are used in the experiment.

V. CONCLUSION

The aim of this study was to answer the following questions. What is the effect of the traffic situation on lane change behaviour, in terms of lane change duration and steering behaviour? And, how does this effect relate to the inter- and intra-driver variability in lane change behaviour? Furthermore, does the lane change duration correlate with the steering behaviour during the lane change?

First of all, the lane change duration does not determine the steering behaviour during a lane change. Although the lane change duration and steering behaviour are mildly correlated (R=-.48, R=-.52, R=-.48, R=-.37), a known lane change duration does not determine steering behaviour. Additionally, the lane change duration is difficult to determine. It is therefore proposed that trajectories should be based on the steering behaviour due to its relation with haptic and vestibular feedback.

Secondly, no effect of the traffic scenario on the lane change behaviour was found. Partly due to the ability of the participants to influence the traffic by adjusting the timing of the lane change. And partly due to the high inter- and intra-driver variability in lane change behaviour. Looking at the spatial context, it seems that drivers exhibit high variability in lane change duration when spatio-temporal criticality is low. Higher spatio-temporal criticality limits the drivers in their lane change duration. Data implies that drivers keep a minimum safety margin of TTC=2 s at the time of lane crossing with respect to the slow lead vehicle.

Lastly, in relation to the effect of the traffic scenario, both inter- and intra-driver variability are relatively high. Therefore, the traffic situation is an unreliable predictor of lane change behaviour on its own. Additionally, creating personalized lane change trajectories only mitigates the inter-driver variability. In order to mitigate intra-driver variability in assistance systems, adaptable trajectories could be created that can be adapted during the manoeuvre.

Future work should determine if the variability exhibited by drivers is a matter of preference, or a matter of indifference. Knowing this would influence the implementation of human-like trajectories in assistance systems tremendously. The need for mitigating intra-driver variability is eliminated if drivers are known to exhibit high variability due to indifference, as opposed to preference. Furthermore, human-like lane change trajectories based on steering behaviour should be implemented and tested in lane change support systems in order to assess whether such lane change assistance systems indeed increase acceptance by drivers.

ACKNOWLEDGMENT

The research project is supported by Cruden BV.

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Appendix A

Determining lane change duration

A-1 $\mathbf{t_{start}}$ and $\mathbf{t_{end}}$

Determining the duration of the lane change starts with determining a clear start and end point of the manoeuvre. As has been stated before, literature does not provide a consistent view on the matter. In literature a wide variety of methods for determining the start and ending of the lane change manouevre are used, complicating comparisons between studies [1]. For example: Salvucci [2] studied the time course of a lane change and let participants indicate verbally the intention to change lanes. Hetrick [3] indicated the start and end of the lane change manually by looking at the lateral position and steering wheel angle.

Therefore, a novel way of determining the start and endpoints of the lane change is demonstrated here. The starting point of the lane change is determined based on the steering movement which starts the lane change. Therefore, the criterion for the start of the lane change is based on the steering wheel angle and steering wheel rate as opposed to other methods using the lateral position.

Starting with the start point, figure A-1 shows that the lane change starts with the steering action. Therefore, the start of the lane change is defined as the last moment before θ_{max} in which the following criteria hold:

$$\theta(t_{start}) < \frac{1}{2}\theta_{max} \tag{A-1}$$

and

$$\dot{\theta}(t_{start}) < 0.1 \text{ deg/s} \tag{A-2}$$

and

$$y_{offset}(t_{start}) < 0.5 \text{ m} \tag{A-3}$$

With y_{offset} being the lateral distance to the lane center of the current lane. With θ being the steering wheel angle, θ_{max} being the maximum steering wheel angle of the first steering

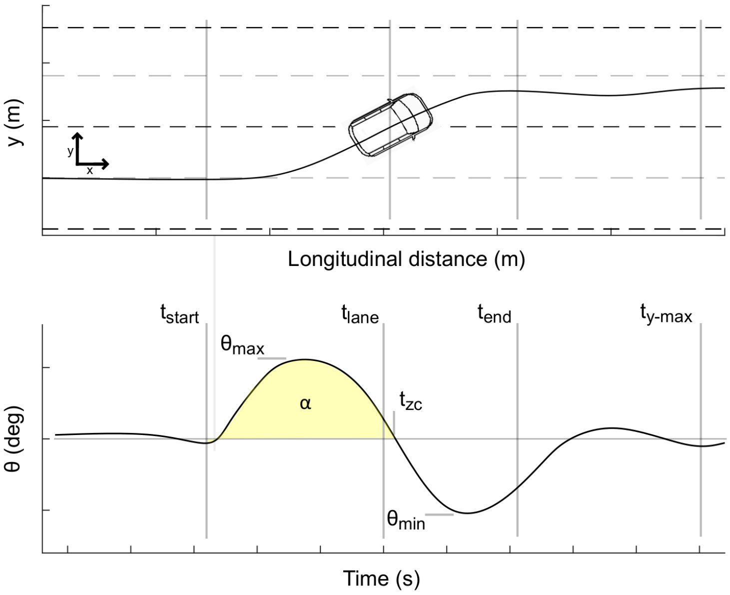

Figure A-1: Lane change trajectory with corresponding steering wheel angle and visualization of the lane change duration and steering characteristics.

peak and $\dot{\theta}$ is the steering wheel rate. Thus, the start of the lane change is defined as the beginning of the first steering wheel peak.

Equation A-1 is used to make sure that the lane change start is determined well before the peak steering wheel angle θ_{max} is reached. The factor of one half is determined empirically. In choosing this factor, a trade-off has to be made between: detecting a lane change at the earliest moment (a low threshold) and falsely detecting lane changes that could still be considered as lane keeping (high threshold). It is chosen to use a relatively high threshold with a factor of one half to eliminate false detection and diminish variability in lane change duration.

Equation A-2 makes sure that the t_{start} is determined at the beginning of a steering action.

Equation A-3 is used to determine the correct start of the lane change when lane changes are made hesitantly. Sometimes a lane change consists of two steering in phases during a lane change, in this case the start of the lane change is the last moment which satisfies the other two criteria and starts within 0.5 m of the lane center.

In figure A-2, A-3 and A-4 the start points are indicated for participant 3, 7 and 20. As can already be seen from the steering behaviour in these figures, the ending of the lane change is less clear than the start of the lane change. Therefore, a different approach is used to determine the end of the lane change as can be seen from equation A-4 and A-5. The heading is used to determine the end of the lane change. The end of the lane change is determined as the first point for which the following criteria are met:

$$\psi(t_{end}) < 0.1 \text{ deg} \tag{A-4}$$

and

$$y_{offset}(t_{end}) < 0.4 + 0.5 * y_{offset}(t_{ymax}) \tag{A-5}$$

With $y_{offset}(t_{end})$ the offset to the lane center at the time t_{end} and $y_{offset}(t_{ymax})$ the offset to the lane center at time that the lateral position is maximal. This sets the lateral bandwith in which the first condition should hold: a very small heading (ψ) with respect to the road (equation A-4). The criterion on the heading is used to determine if the lane change has ended and the criterion on the offset is used to filter early endings due to hesitation and allow for people to drive off-center at the same time.

Initially, it was proposed to use the steering behaviour to determine an endpoint of a lane change as well. However, due to the irregular steering behaviour at the end of the lane change this was unsuccessful.

In figure A-2, A-3 and A-4 the end points are indicated for participant 3, 7 and 20.

A-2 Outlier lane changes

After feedback of participants during the pilot study that the driving sessions (3x10 min) were too long and monotonous to keep focus, some alterations were made. In the driving sessions (3x7 min), the overtaking scenarios followed eachother at a higher tempo, mitigating the lack of focus of participants. Additionally, for every driving session an unexpected event was created in order to keep the participants focused and to reduce predictability of the scenarios. Due to the faster sequence of lane change manoeuvres, some manoeuvres were initiated while the vehicle was still recovering from the last manoeuvre. An example can be seen in fig A-5. These lane changes (45 of 630) are not included in data analysis. Partly due to the fact that they are different manoeuvres and partly due to the fact that no clear start of the lane change can be determined for these manoeuvres. The criterion that is used to determine if manouevres are outliers: if the EV is not in the right lane 10 seconds before the EV crosses the line to the left lane, the manoeuvre is removed from the data set.

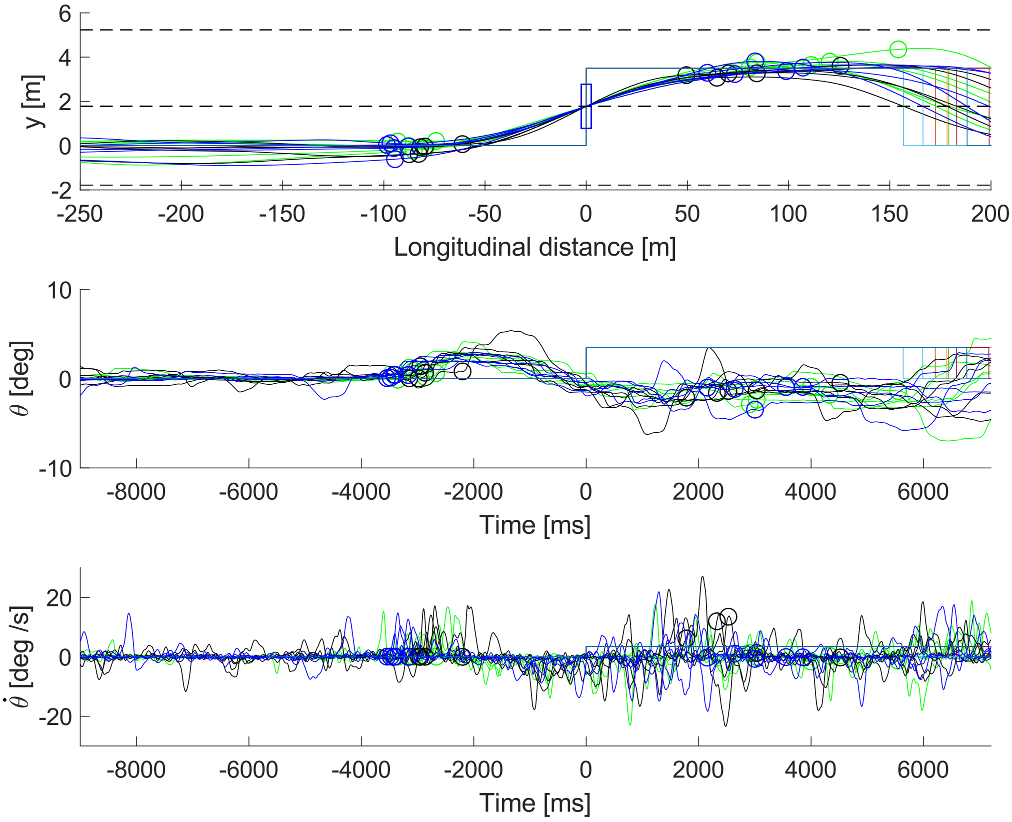

Figure A-2: Lane change trajectories with corresponding steering wheel angle and steering wheel rate for participant 3. Scenario: $\text{LC}_{\text{ConstantGap}}$. Markers indicate t_{start} and t_{end}.

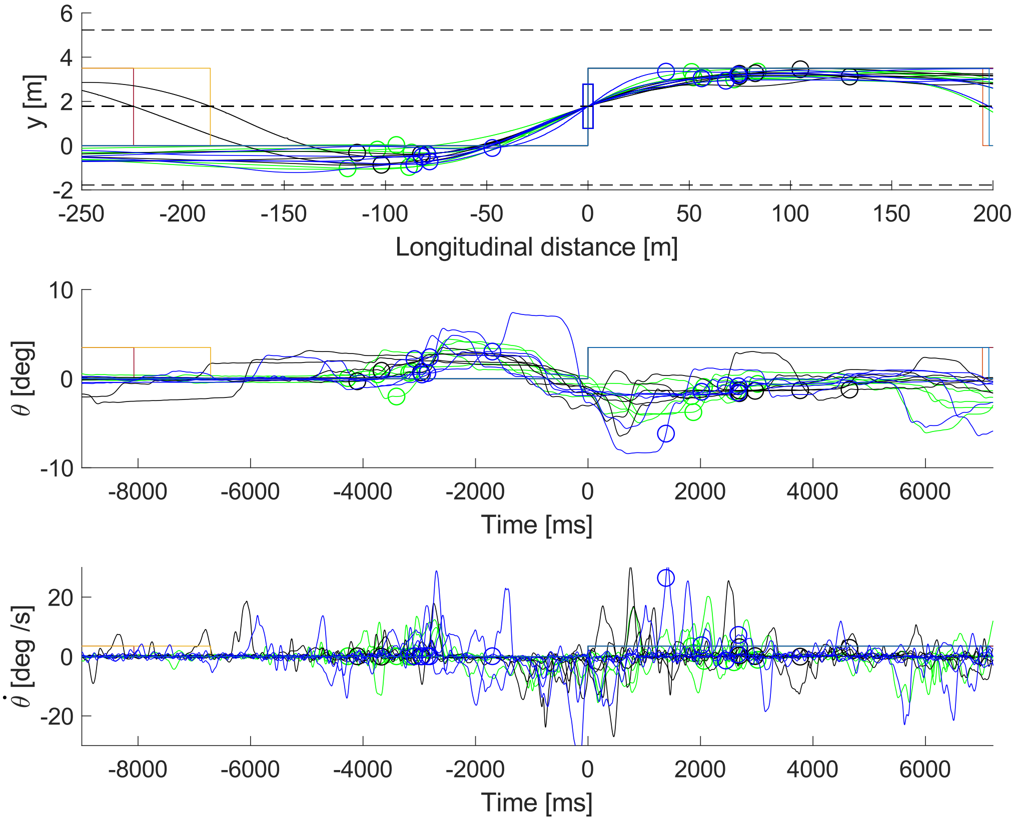

Figure A-3: Lane change trajectories with corresponding steering wheel angle and steering wheel rate for participant 7. Scenario: $\text{LC}_{\text{ConstantGap}}$. Markers indicate t_{start} and t_{end}. Note that two lane change manoeuvres are outliers here and will be removed from data analysis.

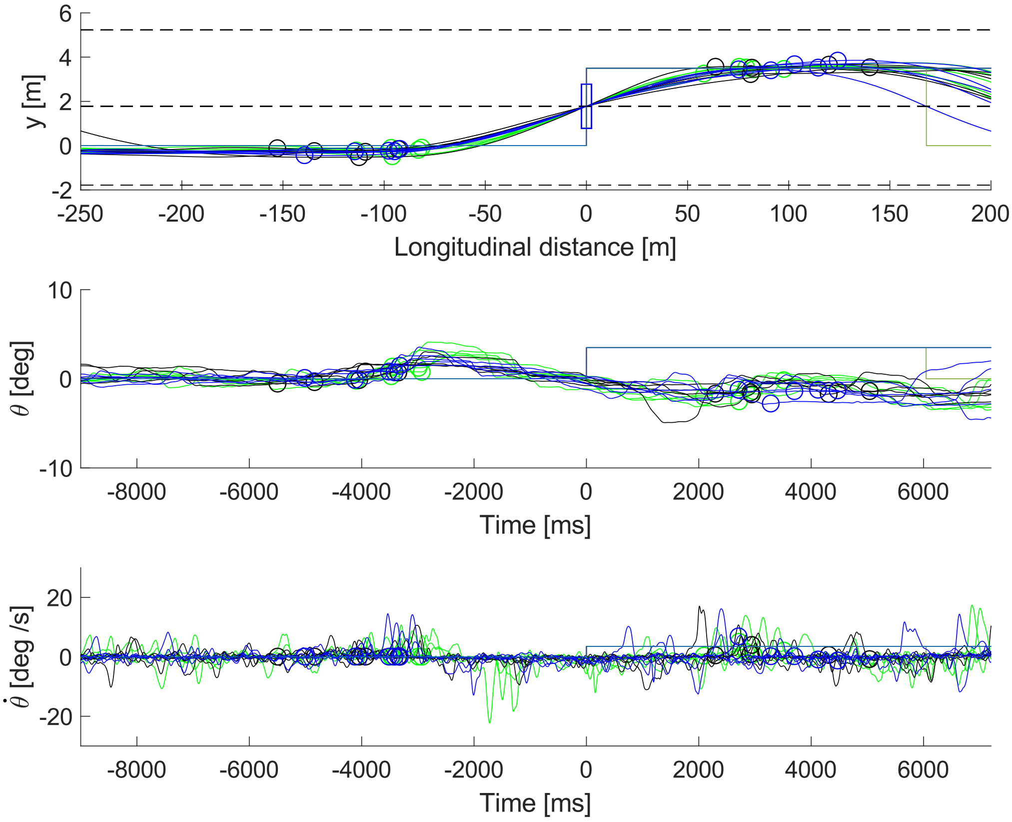

Figure A-4: Lane change trajectories with corresponding steering wheel angle and steering wheel rate for participant 20. Scenario: $\text{LC}_{\text{ConstantGap}}$. Markers indicate t_{start} and t_{end}.

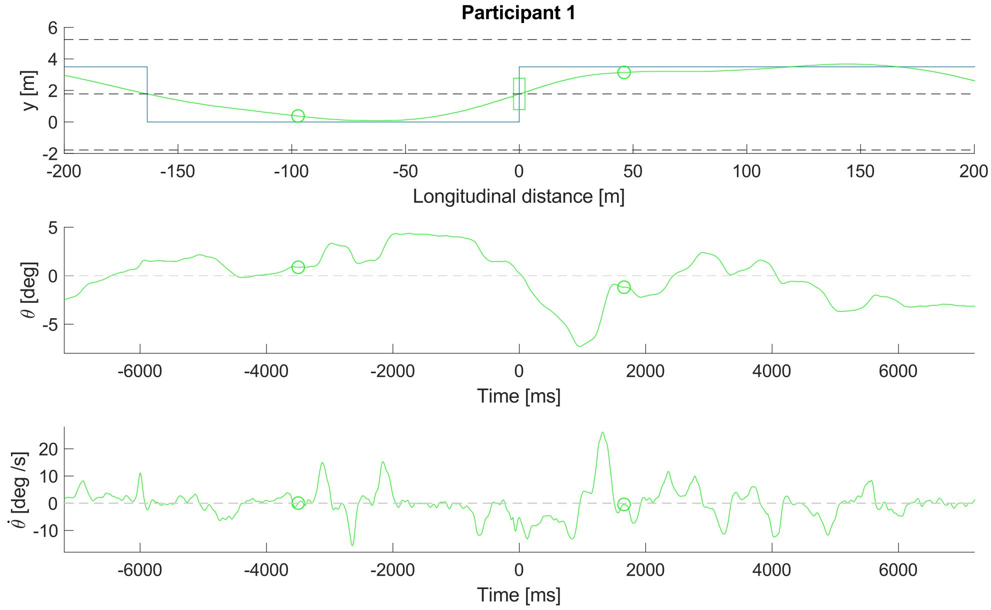

Figure A-5: Lane change trajectory with corresponding steering wheel angle and steering wheel rate for participant 1. This lane change is removed from the data set due to the fact that a "double" lane change is made; the EV is in the left lane 10 seconds before lane crossing to the left lane.

Appendix B

Scenario selection

After conducting a pilot study with 10 conditions, 2 conditions were used for the main experiment. The conditions that were used in the pilot study are reported in table B-1. The conditions in the pilot study were chosen such that the Slow Lead Vehicle (SLV) would not be the most critical during the lane change manoeuvre. It was hypothesized that creating scenarios that are critical with respect to the SLV would pressure drivers into executing a manoeuvre based on safety constraints rather than on personal preference in driving behaviour. Therefore, the TTC to the SLV was kept relatively high (13.5 s, non-critical) compared to the TTC to the TFV for the more critical scenarios. Thus, the independent variable would be the distance to and speed of the TFV delimiting the gap in the target lane.

However, two problems occurred during the pilot study. Firstly, people did not change lanes into the designated target gap in situations with more critical TTC from TFV to EV. This was due to the fact that the manoeuvre became too stressful compared to the TTC to the slow lead vehicle. In normal driving conditions it would be possible to let the TFV pass before changing lanes. Secondly, in conditions with low TTC from TFV to EV drivers started their lane changes after the TFV had already slowed down (increasing the TTC) in order not to collide with the EV. This altered the scenarios in such a way that they could not be objectively compared anymore.

Additionally, during the pilot study, the overtaking scenarios were separated by a one minute initialization phase for the next lane change. However, participants commented that this was too long to stay focused on the driving task and that they lost interest and focus. Furthermore, the use of 10 different scenarios resulted in only 3 repetitions per participant per scenario, which would not be enough for the main experiment.

In order to mitigate these problems, 2 driving scenarios were used during the main experiment, resulting in 15 repetitions per participant per scenario. In order to create scenarios that are less than 1 minute apart, the LV was introduced driving at the same speed as the EV in front of the EV (THW $\approx$ 2 s), as can be seen from figure B-1. When, the LV starts the lane change, the SLV is revealed driving at 72 km/h. This gives the incentive for the EV to change lanes. Two scenarios are created in which the velocity of the TFV is the independent variable. In

Table B-1: Velocity of Target Following Vehicle (TFV) and distance from TFV to Ego Vehicle (EV). TTC from TFV to EV is reported in the corresponding cells.

	D_{TFV}		
V_{TFV}	25 m	35 m	50 m
100 kmh	TTC inf	TTC inf	x
105 kmh	TTC 18 s	TTC 25.2 s	TTC 36 s
110 kmh	TTC 9 s	TTC 12.6 s	TTC 18 s
125 kmh	x	TTC 5 s	TTC 7.2 s

order to be able to create 2 sufficiently different scenarios without creating critical scenarios that result in behaviour as in the pilot experiment, a scenario with a constant relatively large gap and a scenario with a closing gap in the target lane were chosen.

$LC_{ConstantGap}$: the gap between the TFV and the EV is constant, meaning that the TFV is driving at 100 km/h at a constant distance of 45 m. The TTC is therefore infinite (see B-2) and the THW is 1.62 s.

$LC_{ClosingGap}$: in this condition the gap between the TFV and the EV is closing. The TFV is driving at 105 km/h starting at a distance of 45 m. The acceleration from 100 km/h to 105 km/h starts before the lane change of the LV such that the velocity of the TFV has reached 105 km/h when the LV starts changing lanes and the driver checks his/her mirrors. Therefore the distance between EV and TFV at the time of start of the lane change of LV is 40 m. The TTC between the TFV and EV at this moment, the first moment that the incentive to change lanes is present, is 28.8 s and the THW is 1.37 s.

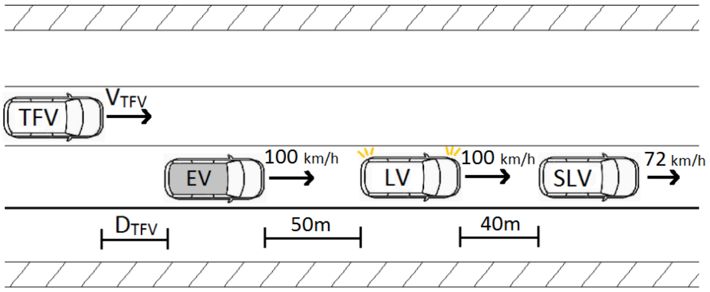

Figure B-1: Generic scenario visualisation for the main experiment at the start of the lane change of the LV. This is the time that $D_{TFV}(t_{start})$ is measured.

Table B-2: Lane change scenarios (LC) with corresponding time to collision (TTC) and time headway (THW) between TFV and EV

Scenario	V_{TFV} [km/h]	D_{TFV} [m]	TTC [s]	THW [s]
$LC_{ClosingGap}$	105	40	28.8	1.37
$LC_{ConstantGap}$	100	45	inf	1.62

Appendix C

Additional results and figures

C-1 Distribution plots

In the figures below (figure C-1, C-2, C-3, C-4, C-5, C-6) the distribution plots can be seen for the lane change duration and steering behaviour.

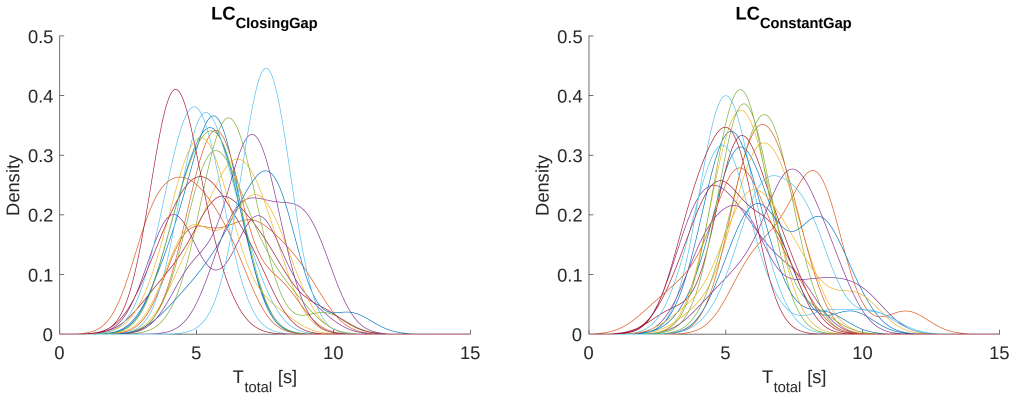

Figure C-1: Kernel density estimate of the lane change duration T_{total} per participant for LC$_{\text{closing}}$ and LC$_{\text{free}}$ with bandwidth 0.8 s.

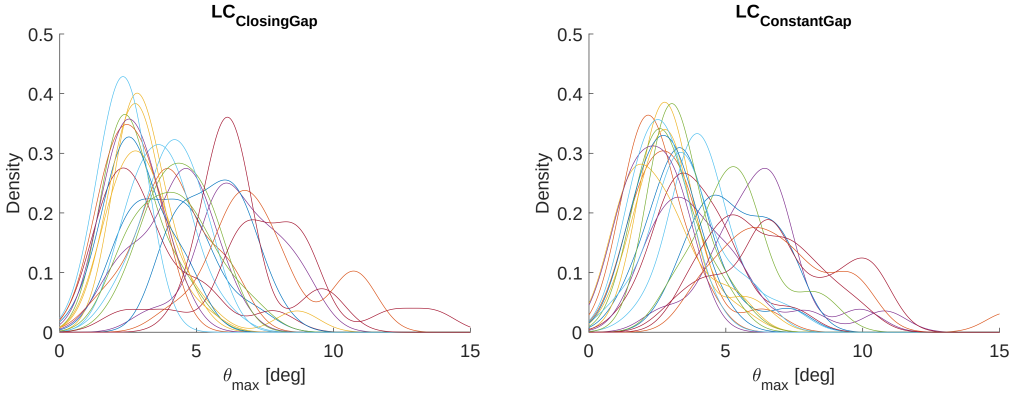

Figure C-2: Kernel density estimate of the maximum steering wheel angle θ_{max} per participant for LC$_{\text{closing}}$ and LC$_{\text{free}}$ with bandwidth 0.8 deg.

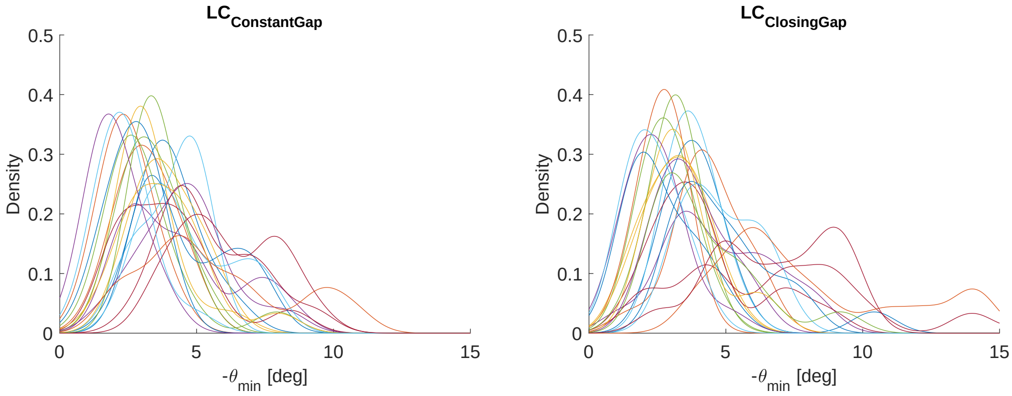

Figure C-3: Kernel density estimate of the minimum steering wheel angle θ_{max} per participant for LC$_{\text{closing}}$ and LC$_{\text{free}}$ with bandwidth 0.8 deg.

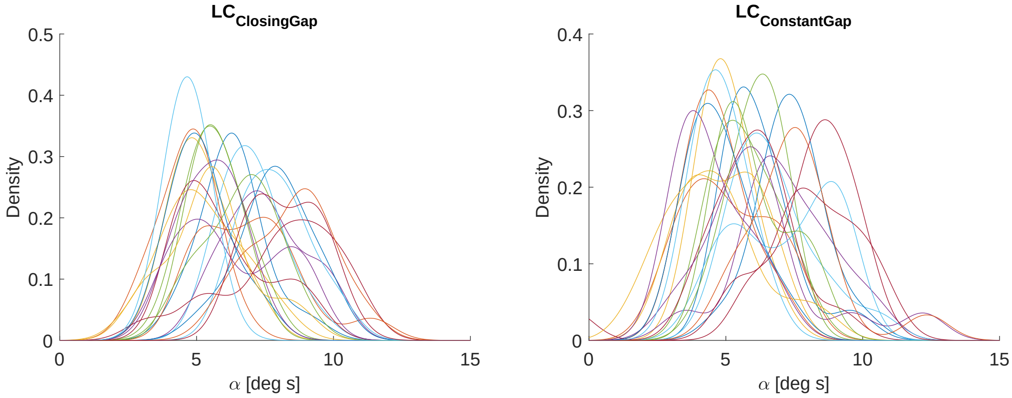

Figure C-4: Kernel density estimate of the integral of the steering wheel angle α per participant for LC$_{\text{closing}}$ and LC$_{\text{free}}$ with bandwidth 0.8 deg s.

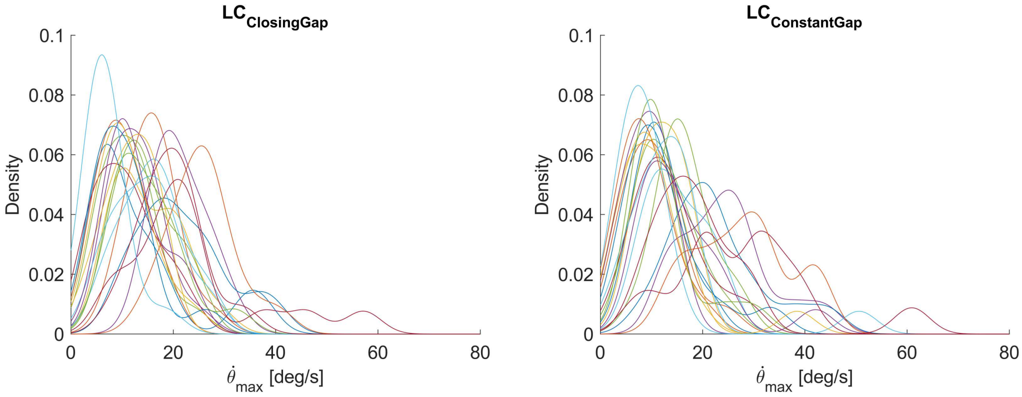

Figure C-5: Kernel density estimate of the maximum steering wheel velocity $\dot{\theta}_{max}$ per participant for LC$_{\text{closing}}$ and LC$_{\text{free}}$ with bandwidth 3.5 deg/s.

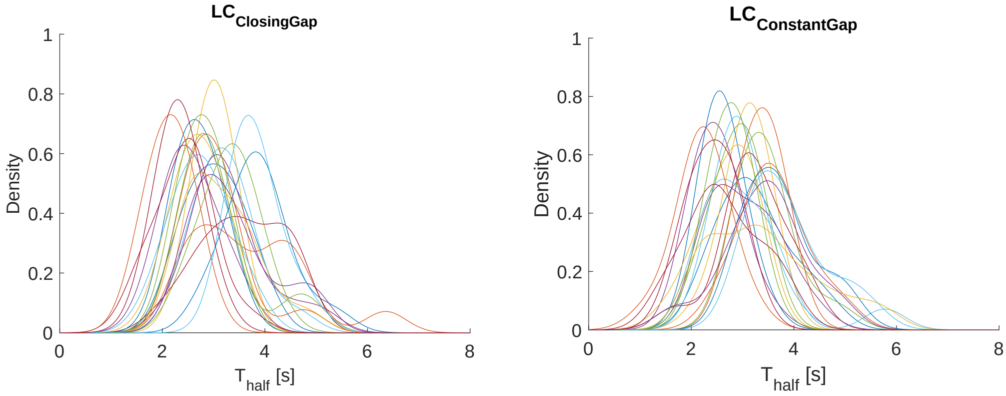

Figure C-6: Kernel density estimate of the half lane change duration T_{half} per participant for LC$_{\text{closing}}$ and LC$_{\text{free}}$ with bandwidth 0.4 s.

C-2 Main effects

In this section, the plots showing the main effects of the scenario will be displayed. Note that only α shows a significant effect, albeit a small effect with respect to inter- and intra-driver variability.

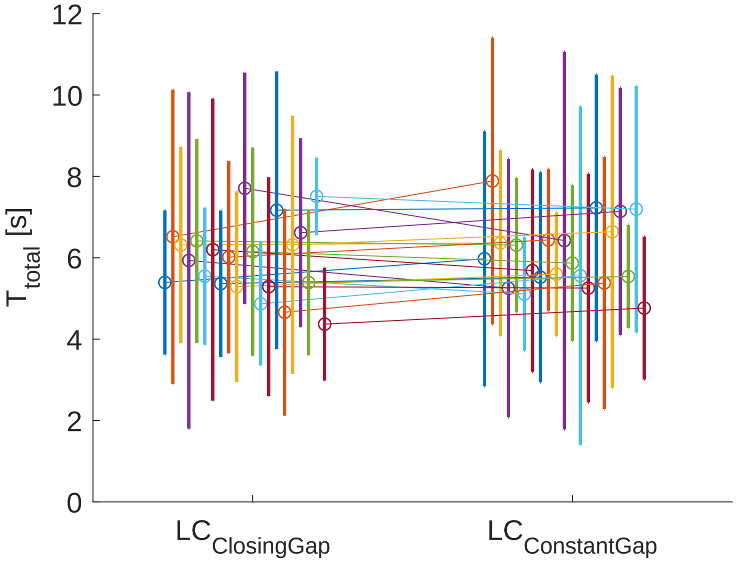

Figure C-7: Mean and 95% prediction interval per participant for both scenarios for T_{total}. Means of participants of both scenarios are connected by lines. There was no significant difference in T_{total} for $LC_{closing}$ (M=6.23, SD=0.89) and LC_{free} (M=6.45, SD=0.90) conditions; t(20)=-1.60, p=0.14, d=0.35.

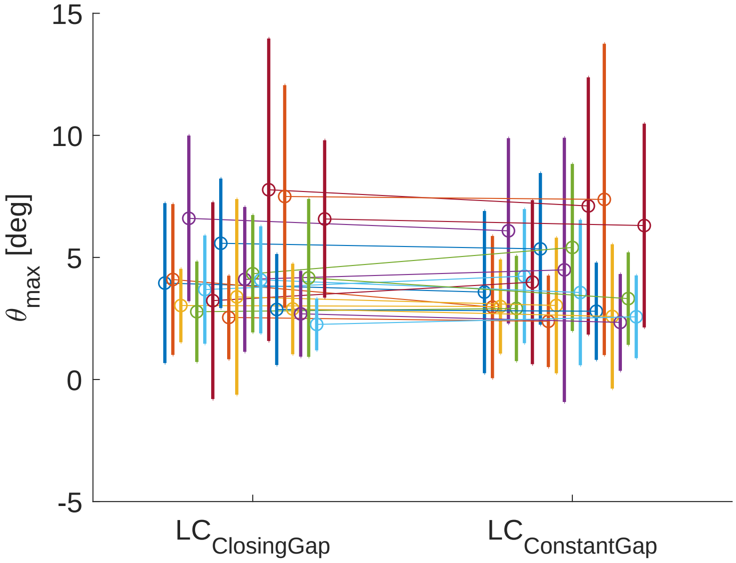

Figure C-8: Mean and 95% prediction interval per participant for both scenarios for θ_{max}. Means of participants of both scenarios are connected by lines. There was no significant difference in θ_{max} for $LC_{closing}$ (M=4.20, SD=1.65) and LC_{free} (M=4.07, SD=1.59) conditions; t(20)=1.12, p=0.27, d=0.25.

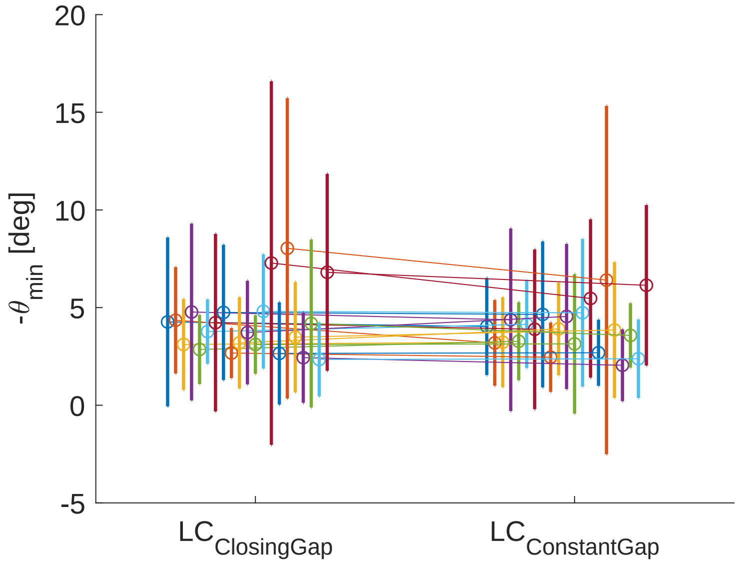

Figure C-9: Mean and 95% prediction interval per participant for both scenarios for $theta_{min}$. Means of participants of both scenarios are connected by lines. There was no significant difference in $-\theta_{min}$ for $\mathrm{LC}_{\mathrm{closing}}$ (M=4.14, SD=1.57) and $\mathrm{LC}_{\mathrm{free}}$ (M=3.91, SD=1.16) conditions; t(20)=1.51, p=0.15, d=0.33.

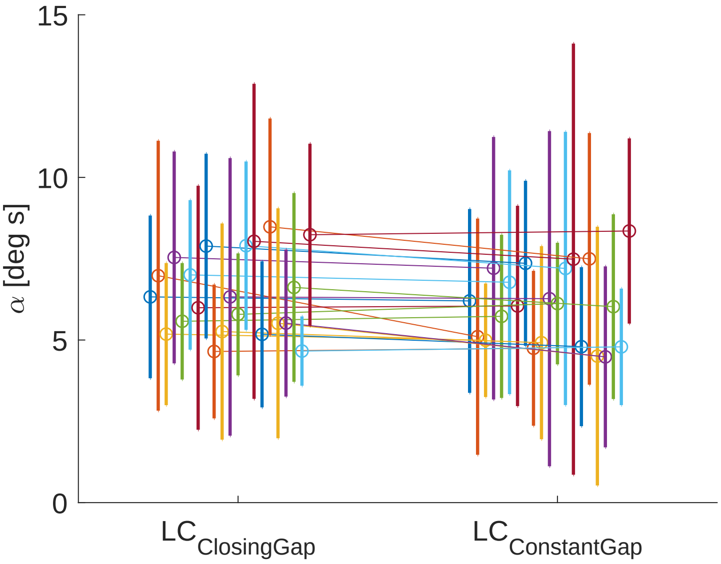

Figure C-10: Mean and 95% prediction interval per participant for both scenarios for α. Means of participants of both scenarios are connected by lines. There was no significant difference in α for $\mathrm{LC}_{\mathrm{closing}}$ (M=6.64, SD=1.24) and $\mathrm{LC}_{\mathrm{free}}$ (M=6.37, SD=1.20) conditions; t(20)=2.44, p=0.024, d=0.53.

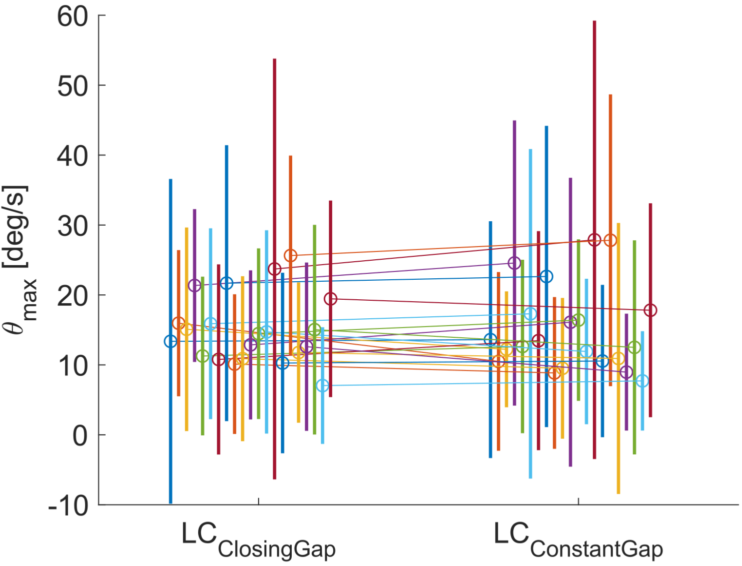

Figure C-11: Mean and 95% prediction interval per participant for both scenarios for $\dot{\theta}_{max}$. Means of participants of both scenarios are connected by lines. There was no significant difference in $\dot{\theta}_{max}$ for LC$_{\text{closing}}$ (M=15.2, SD=4.78) and LC$_{\text{free}}$ (M=15.3, SD=6.08) conditions; t(20)=-0.12, p=0.90, d=-0.027.

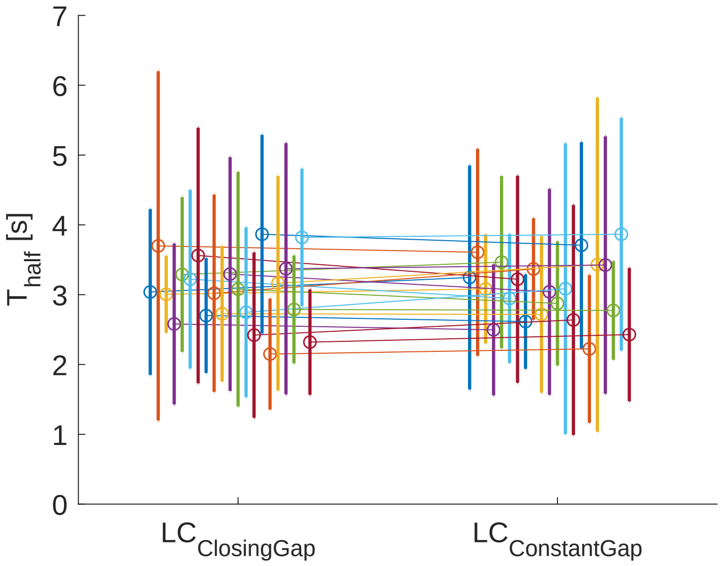

Figure C-12: Mean and 95% prediction interval per participant for both scenarios for T_{half}. Means of participants of both scenarios are connected by lines. There was no significant difference in T_{half} for LC$_{\text{closing}}$ (M=3.04, SD=0.48) and LC$_{\text{free}}$ (M=3.06, SD=0.45) conditions; t(20)=0.43, p=0.67, d=-0.094.

Table C-1: Pearson correlation coefficients r shown below the diagonal, p-value corresponding to the correlation shown above the diagonal (n=585). (n=288) for correlations with $D_{SLV}(t_{start})$. For correlations with $D_{TFV}(t_{start})$ only $LC_{ClosingGap}$ is used (n=293).

	T_{half}	T_{total}	θ_{max}	$-\theta_{min}$	α	$\dot{\theta}_{max}$	$D_{SLV}(t_{start})$	$D_{TFV}(t_{start})$
T_{half}	-	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004
T_{total}	0.71	-	<0.001	<0.001	<0.001	<0.001	<0.001	0.046
θ_{max}	-0.61	-0.48	-	<0.001	<0.001	<0.001	<0.001	0.15
$-\theta_{min}$	-0.49	-0.52	0.66	-	<0.001	<0.001	<0.001	0.005
α	-0.37	-0.48	0.72	0.67	-	<0.001	0.024	0.90
$\dot{\theta}_{max}$	-0.47	-0.37	0.77	0.48	0.57	-	<0.001	0.014
$D_{SLV}(t_{start})$	0.34	0.35	-0.28	-0.30	-0.12	-0.21	-	0.016
$D_{TFV}(t_{start})$	0.17	0.12	-0.084	-0.16	0.0077	-0.14	0.19	-

Table C-2: Spearmna correlation coefficients r shown below the diagonal, p-value corresponding to the correlation shown above the diagonal (n=585). (n=288) for correlations with $D_{SLV}(t_{start})$. For correlations with $D_{TFV}(t_{start})$ only $LC_{ClosingGap}$ is used (n=293).

	T_{half}	T_{total}	θ_{max}	$-\theta_{min}$	α	$\dot{\theta}_{max}$	$D_{SLV}(t_{start})$	$D_{TFV}(t_{start})$
T_{half}	-	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004
T_{total}	0.70	-	<0.001	<0.001	<0.001	<0.001	<0.001	0.017
θ_{max}	-0.67	-0.54	-	<0.001	<0.001	<0.001	0.003	0.11
$-\theta_{min}$	-0.51	-0.58	0.61	-	<0.001	<0.001	<0.001	0.027
α	-0.41	-0.52	0.76	0.69	-	<0.001	0.076	0.89
$\dot{\theta}_{max}$	-0.50	-0.40	0.77	0.47	0.65	-	0.005	0.084
$D_{SLV}(t_{start})$	0.25	0.29	-0.16	-0.19	-0.10	-0.15	-	<0.001
$D_{TFV}(t_{start})$	0.17	0.14	-0.094	-0.13	0.0078	-0.10	0.29	-

C-3 Correlation plots of variables

This section will show the scatter plots of the variables, showing correlations between them. Starting with the steering behaviour and lane change duration. The Pearson and Spearman correlations can be seen in table C-1 and C-2 respectively. The Pearson correlation is a measure of the linear correlation of two variables, whereas the Spearman correlation evaluates the monotonic relationship. This means that the Spearman correlation indicates a relationship between two variables that is not necessarily linear, but is monotonic. The Spearman correlation is shown here in addition to the Pearson correlation since the relationship between duration and steering behaviour metrics does not always seem completely linear. As can be seen, only slight differences between the Pearson and Spearman correlations are found.

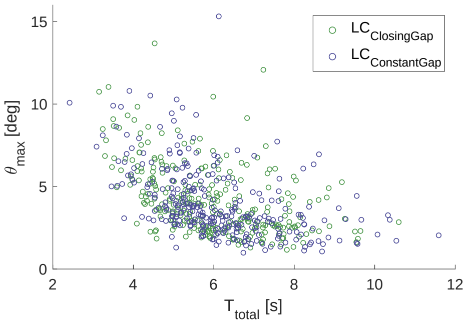

Figure C-13: T_{total} versus θ_{max} for all participants per scenario.

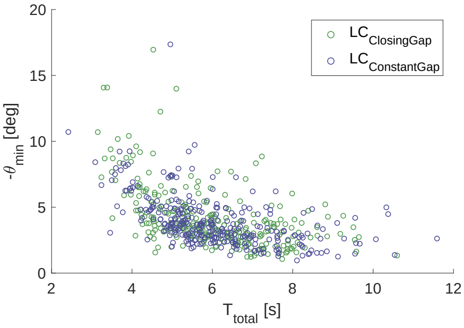

Figure C-14: T_{total} versus θ_{min} for all participants per scenario.

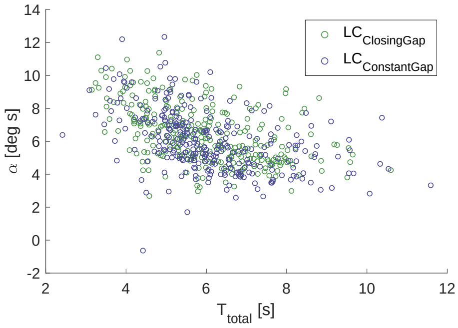

Figure C-15: T_{total} versus α for all participants per scenario.

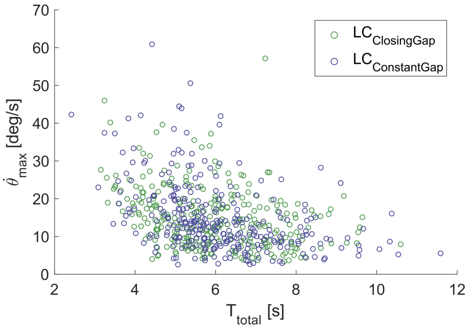

Figure C-16: T_{total} versus $\dot{\theta}_{max}$ for all participants per scenario.

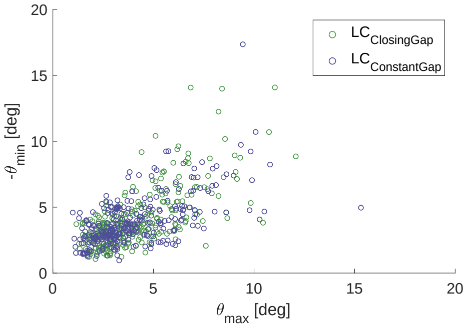

Figure C-17: θ_{max} versus θ_{min} for all participants per scenario.

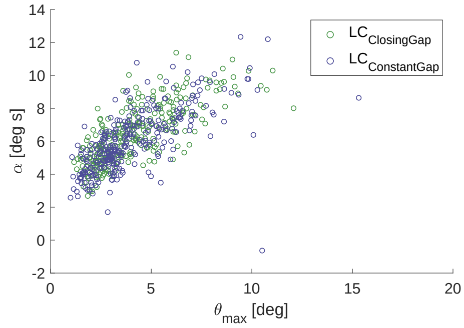

Figure C-18: θ_{max} versus α for all participants per scenario.

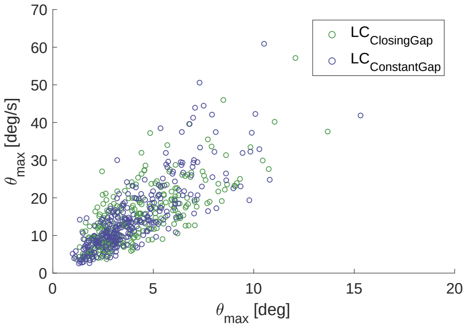

Figure C-19: θ_{max} versus $\dot{\theta}_{max}$ for all participants per scenario.

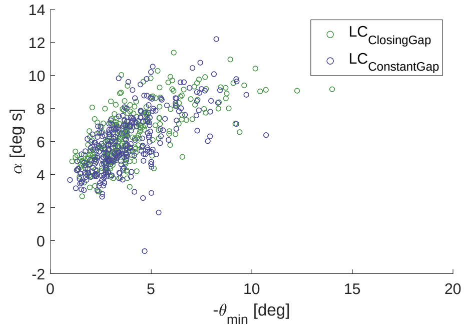

Figure C-20: θ_{min} versus α for all participants per scenario.

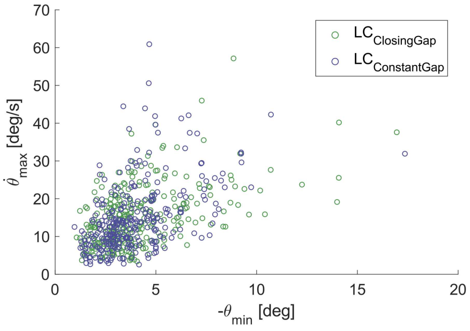

Figure C-21: θ_{min} versus $\dot{\theta}_{max}$ for all participants per scenario.

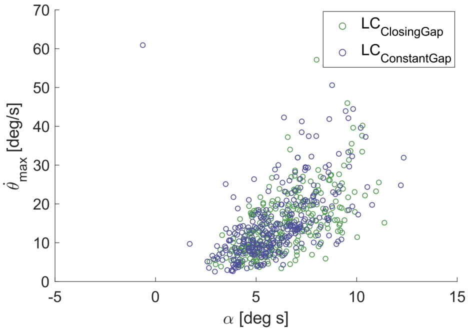

Figure C-22: α versus $\dot{\theta}_{max}$ for all participants per scenario.

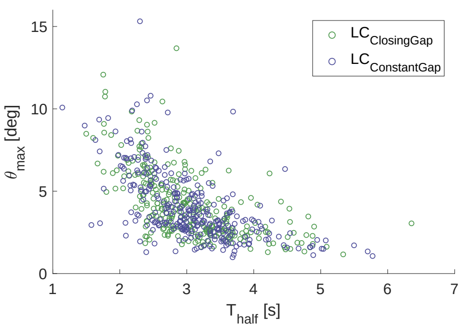

Figure C-23: T_{half} versus θ_{max} for all participants per scenario.

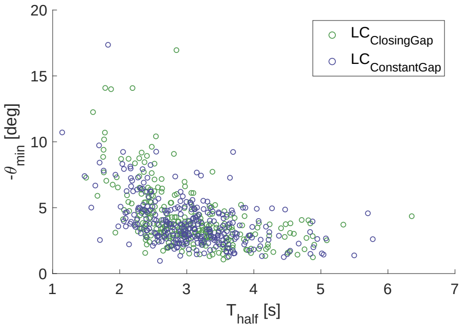

Figure C-24: T_{hafl} versus θ_{min} for all participants per scenario.

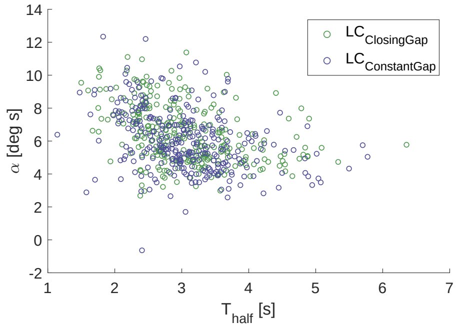

Figure C-25: T_{half} versus α for all participants per scenario.

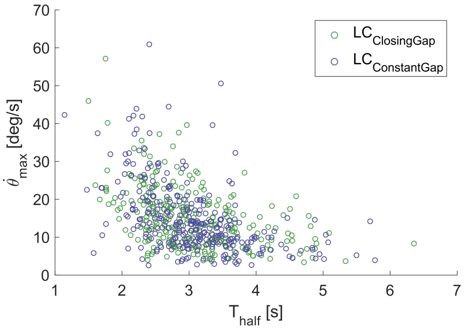

Figure C-26: T_{half} versus $\dot{\theta}_{max}$ for all participants per scenario.

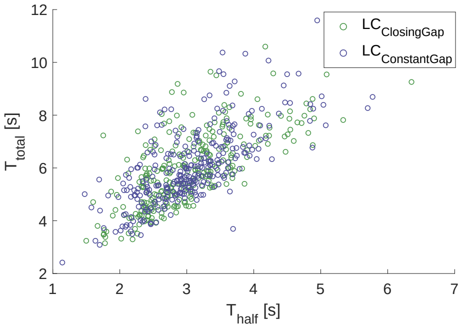

Figure C-27: T_{half} versus T_{total} for all participants per scenario.

Next, the lane change behaviour metrics will be plotted for the spatial context, the distance to SLV and TFV.

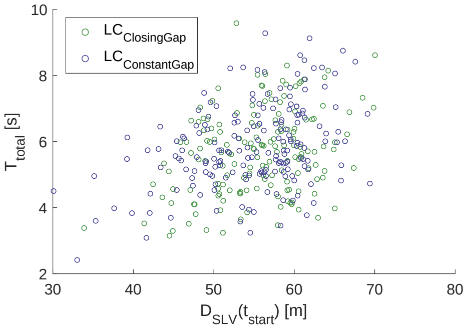

Figure C-28: Distance to the SLV D_{SLV} at time t_{start} versus T_{total} for all participants per scenario. Note that only data is shown that has a distance to the SLV at t_{start}, 288 of 585 lane changes are shown

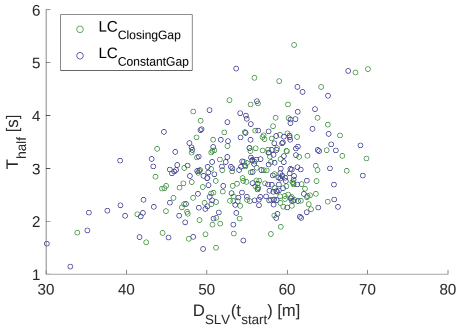

Figure C-29: Distance to the TFV D_{SLV} at time t_{start} versus T_{half} for all participants per scenario.

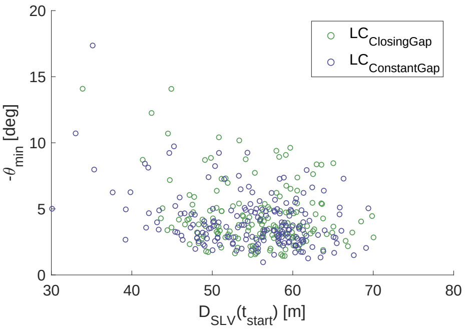

Figure C-30: Distance to the SLV D_{SLV} at time t_{start} versus θ_{min} for all participants per scenario. Note that only data is shown that has a distance to the SLV at t_{start}, 288 of 585 lane changes are shown

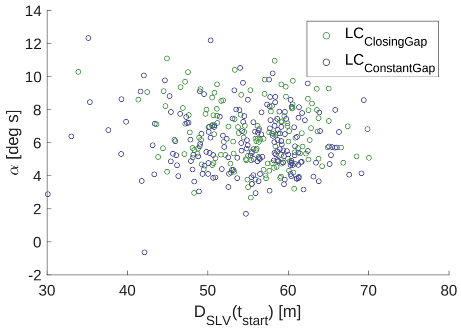

Figure C-31: Distance to the SLV D_{SLV} at time t_{start} versus α for all participants per scenario. Note that only data is shown that has a distance to the SLV at t_{start}, 288 of 585 lane changes are shown

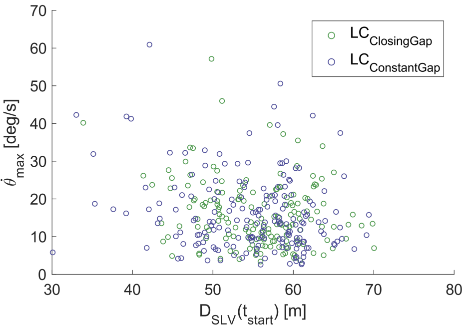

Figure C-32: Distance to the SLV D_{SLV} at time t_{start} versus $\dot{\theta}_{max}$ for all participants per scenario. Note that only data is shown that has a distance to the SLV at t_{start}, 288 of 585 lane changes are shown

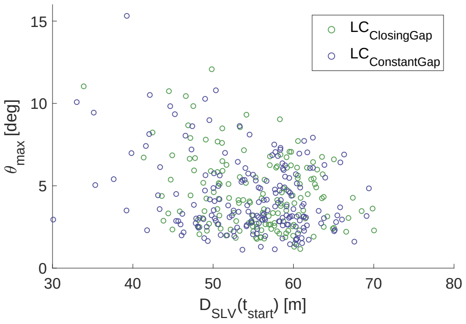

Figure C-33: Distance to the SLV D_{SLV} at time t_{start} versus θ_{max} for all participants per scenario. Note that only data is shown that has a distance to the SLV at t_{start}, 288 of 585 lane changes are shown

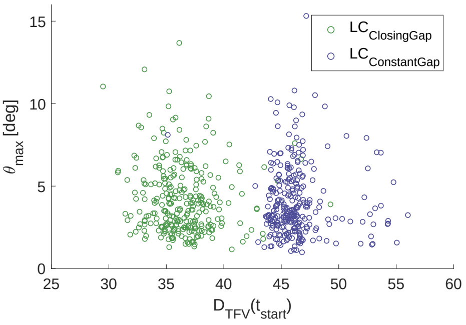

Figure C-34: Distance to the TFV D_{TFV} at time t_{start} versus θ_{max} for all participants per scenario.

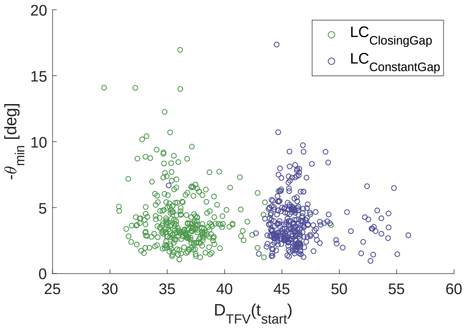

Figure C-35: Distance to the TFV D_{TFV} at time t_{start} versus θ_{min} for all participants per scenario.

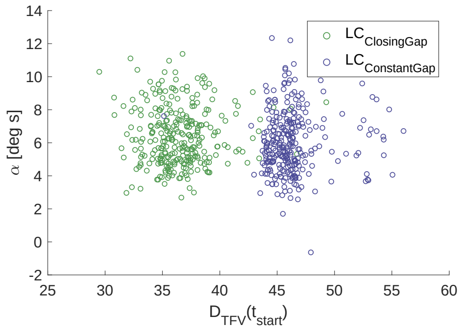

Figure C-36: Distance to the TFV D_{TFV} at time t_{start} versus α for all participants per scenario.

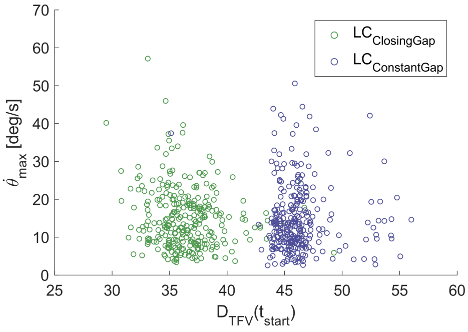

Figure C-37: Distance to the TFV D_{TFV} at time t_{start} versus $\dot{\theta}_{max}$ for all participants per scenario.

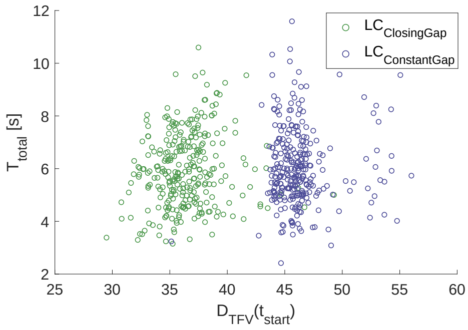

Figure C-38: Distance to the TFV D_{TFV} at time t_{start} versus T_{total} for all participants per scenario.

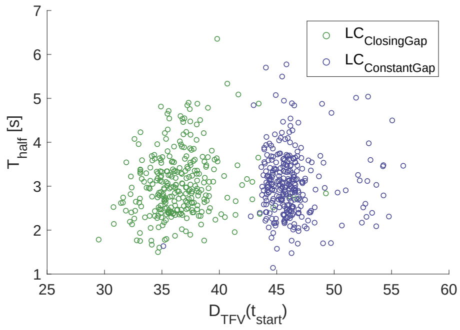

Figure C-39: Distance to the TFV D_{TFV} at time t_{start} versus T_{half} for all participants per scenario.

C-4 Lane change initiation

As can be seen from figure C-40, the effect of the scenario is significant for T_{delay}. Meaning that in the $\text{LC}_{\text{ClosingGap}}$ scenario people will start a lane change approximately 0.4 s earlier on average than in the $\text{LC}_{\text{ConstantGap}}$ scenario. However, some problems arise in the definition of T_{delay}. T_{delay} is defined as the time between the start of the lane change of the EV t_{start} and the time that the LV has moved 2m away from the EV laterally, being effectively out of TTC distance. Therefore, the position on the road of the EV influences T_{delay}. However, from figure C-41 it can be seen that the lateral position of the EV at t_{start} is not influenced by the scenario. However, starting a lane change while the LV is still within these 2 m might result in an LV that never leaves this 2 m area. This is why for some lane change manoeuvres the T_{delay} could not be determined. This resulted in an uneven amount of samples per participant as can be seen from the wide prediction intervals of some participants. The smallest amount of samples of a participant was 9 out of 30. Thus, there is an indication for an effect of the traffic scenario on the timing of the lane change, however this cannot be concluded with certainty.

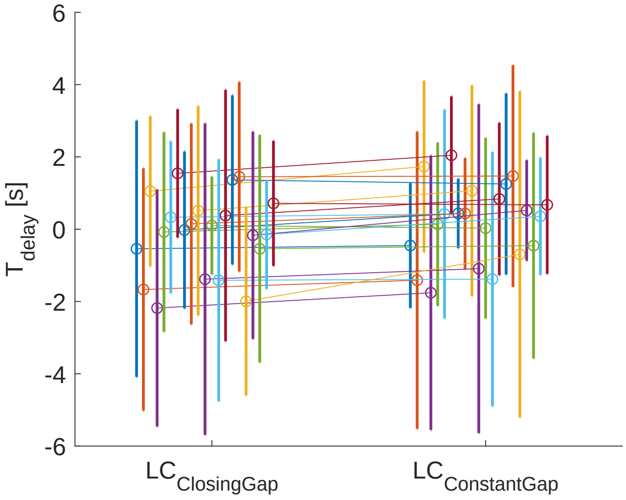

Figure C-40: Mean and 95% prediction interval per participant for both scenarios for T_{total}. Means of participants of both scenarios are connected by lines. There was no significant difference in T_{total} for $LC_{closing}$ (M=-0.12, SD=1.10) and LC_{free} (M=0.20, SD=1.06) conditions; t(20)=-4.39, p<0.001, d=-0.96.

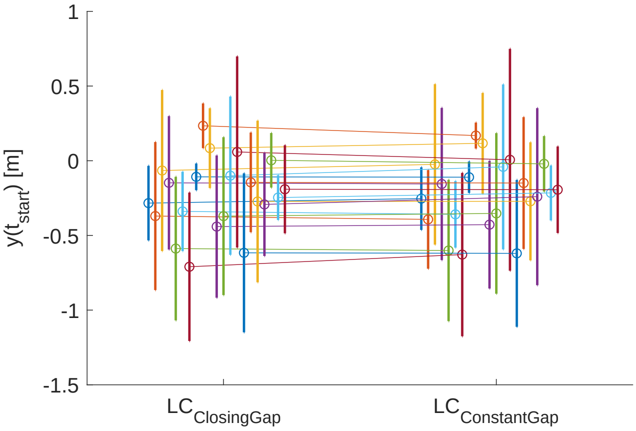

Figure C-41: Mean and 95% prediction interval per participant for both scenarios for T_{total}. Means of participants of both scenarios are connected by lines. There was no significant difference in T_{total} for $LC_{closing}$ (M=-0.23, SD=0.24) and LC_{free} (M=-0.23, SD=0.23) conditions; t(20)=-0.86, p=0.40, d=-0.19.

C-5 Illustrative time traces

Looking at figure C-42, it would be interesting to see what the extreme situations look like in terms of time traces. What makes these lane change durations different? And how does a higher peak steering wheel angle influence the trajectory? This is illustrated here by plotting several of the "extreme" lane changes from figure C-42. What stands out from these graphs is how hard it is to create a universal metric to determine start and end points of a lane change. From figure C-43 it can be seen that the trade off between detecting lane changes early and detecting lane changes falsely results in a lane change that could have been "detected" earlier (LC1). This is the result of the trade off that is made between decreasing variability and detecting lane changes at the earliest moment. For the other two lane changes, note that it is harder to determine the start and end points of a lane change when the steering behaviour during the lane change is very close to the steering behaviour during lane keeping. In other words, for lane changes with lower steering wheel angles and consequently longer lane change durations the start and end points are harder to determine, resulting in more variability in lane change duration.

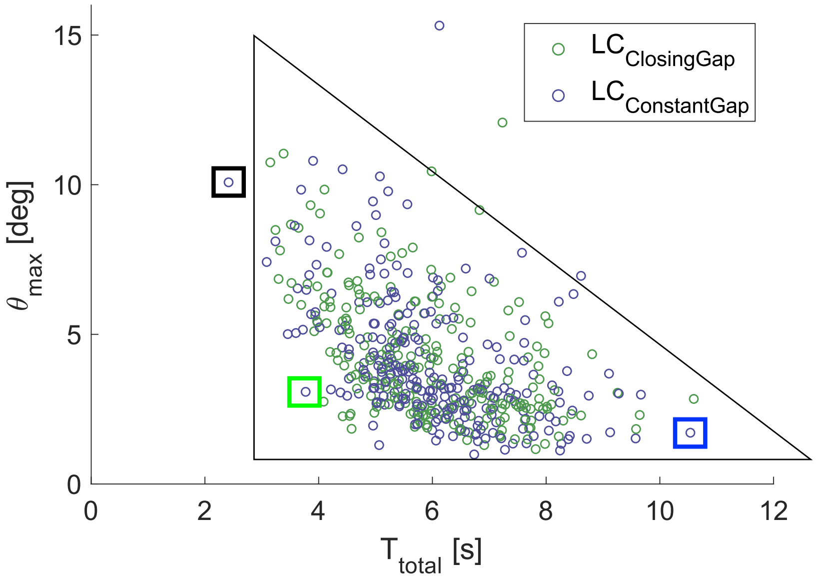

Figure C-42: Peak steering wheel anlge θ_{max} plotted against lane change duration T_{total} for all participants per scenario. Pearson correlation R=-.48. Lane changes that are plotted seperately are indicated by colors. LC1: Black, LC2: Blue, LC3: Green.

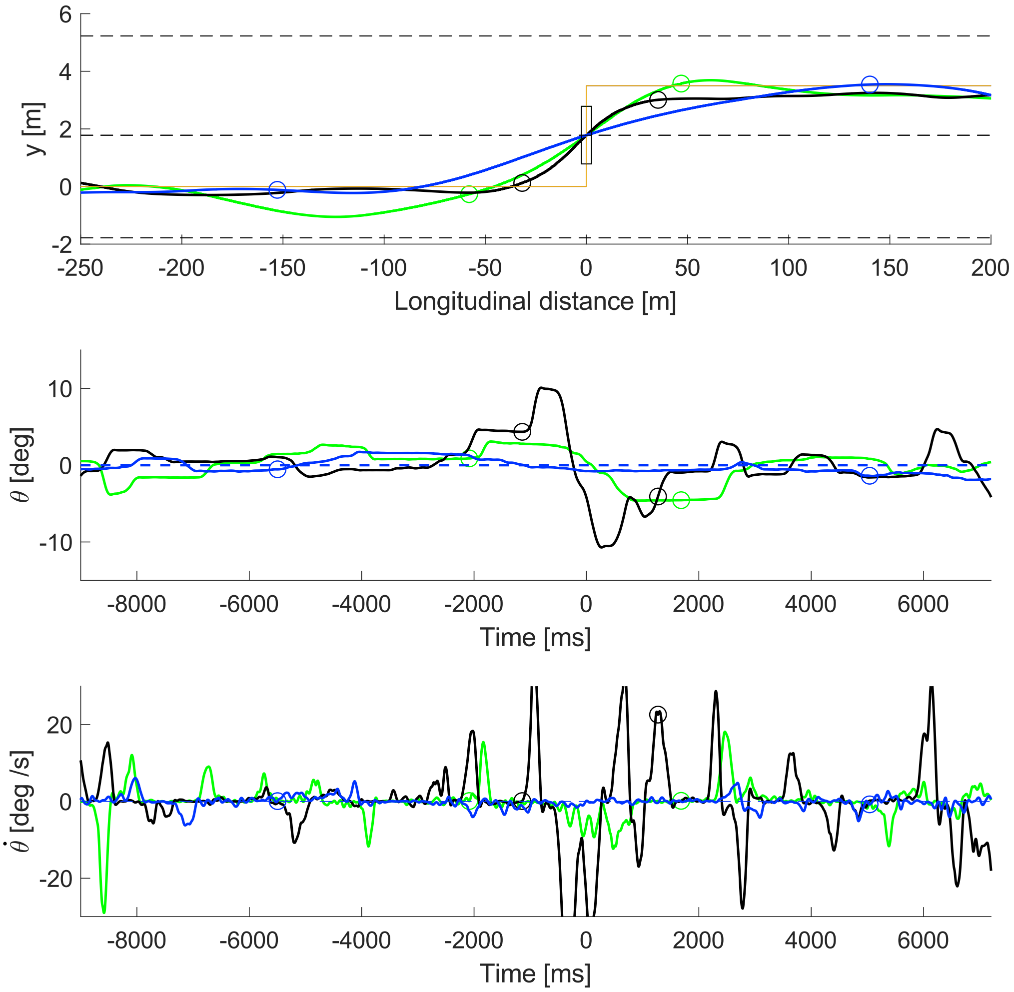

Figure C-43: Lane change trajectories with corresponding steering wheel angle and steering wheel rate for participant 16. LC1: Black, LC2: Blue, LC3: Green. Markers indicate t_{start} and t_{end} .

Appendix D

Informed consent form

1 Research Group

1.1 Researchers in charge of the project

Christiaan Koppel[1]	MSc. Student	Delft University of Technology
Jelle van Doornik[2]	Product manager ADAS	Cruden B.V.
Bastiaan Petermeijer[1]	Post-doctoral Researcher	Delft University of Technology
David Abbink[1]	Full Professor	Delft University of Technology

1.2 Organizations

1. Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, the Netherlands
2. Cruden B.V., Amsterdam, the Netherlands

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2 This document

This Informed Consent Form has two parts:

- **Information Sheet,** pages 1 - 6
- **Certificate of Consent,** page 7

Before agreeing to participate in this study, you are asked to read this document carefully. The Information Sheet describes the purpose, procedures, and risks of this study. After reading the Information Sheet, we will be happy to explain any points that seem unclear, or sections that you do not understand. You should feel comfortable to speak to any of the researchers involved to answer any questions you may have at any time. After you have read this Information Sheet and we have answered all of your questions or discussed any concerns, you can decide if you would like to be involved. At the end of this document, we would like to ask you to sign a written Certificate of Consent to confirm your agreement to participate. Your signature is required for participation.

You will be given a copy of the full Informed Consent Form.

---

3 Purpose of the research

Advanced driver assistance systems (ADAS) are currently being deployed in the majority of new cars. One of these systems is the lane keeping system, which helps the driver to stay in the lane when driving on the highway. This system lowers the workload of the driver and decreases unintentional lane and road departures. To extend this system, a lane change assistance system is proposed. This lane change assistance system helps the driver in executing the lane change manouevre during the transition period from lane keeping to lane changing to lane keeping. The purpose of this research is to gain insight in how human drivers execute a lane change manouevre. This knowledge can then be used to create lane change assistance systems that are compatible with human driving behaviour. This research is done with the aim of contributing to the knowledge of the interaction between driver and ADAS in order to improve safety and comfort of drivers.

---

4 Participation

4.1 Location of the experiment

Participation will involve completing one in-person sessions on different days at Cruden B.V. Global Headquarters, Pedro de Medinalaan 25, 1086 XP Amsterdam, the Netherlands.

4.2 Eligibility criteria

You are invited to participate in this project if:

- You are 18 years or older.
- You have a car driving license.
- You have normal or corrected-to-normal vision (i.e. glasses or contact lenses).
- You have not experienced severe (simulator) motion sickness in the past.
- You do not have heart, back or neck issues.
- You have not been diagnosed with epilepsy.
- You are not pregnant.
- You have not recently had surgery.
- You are not physically disabled.
- You are not under the influence of drugs, alcohol or prescription substances that may compromise the comfort when operating a motion-based driving simulator.

The researchers reserve the right at any time to refuse or excuse (from an in-progress session) any participant who does not meet/no longer meets the study requirements or who are behaving in an unnecessarily unsafe manner.

4.3 Voluntary participation and right to refuse or withdraw

Your participation in this project is completely voluntary. We welcome you to contact us to ask any questions and to discuss your possible involvement in the project, but it is your choice whether to participate or not. If you do agree to participate you have the right to withdraw from the project at any moment without comment or penalty.

5 Procedure

The research consists of 1 driving simulator experiment. The experiment will retrieve lane change data with the aim of analysing human driving behaviour. The driving data will be logged by the driving simulator.

5.1 Experiment

You will be asked to perform three driving sessions (3x10 min) in a highway setting. Data from this experiment will be used to analyze human lane change behaviour. The simulated vehicle is a generic sedan car. The simulated vehicle is controlled in the same way as a normal car driving on cruise control: steering wheel, turn signals. A dashboard with speedometer is available as well as two side view mirrors and one rear view mirror.

5.2 Prior to the simulator sessions

Prior to the simulator sessions, the informed consent form will be sent to you. When you visit the simulator sessions, the study details will be explained to you, an informed consent form will be signed, and a demographics questionnaire will be completed.
Next, a safety instruction will be given on operating the driving simulator.

5.3 Practice simulator session

The experiment will start with some practice to familiarize yourself with the simulator, the virtual environment and the procedure of starting an experiment. The practice session, for both experiments, takes around 5 minutes and you are encouraged to drive both fast and slow to get a feeling of the dynamics of the vehicle.

5.4 Simulator session instructions

5.4.1 Driving

During the experiment, you are asked to drive as you normally would and to respect the traffic regulations. Drivers will drive in the right lane, unless overtaking slower vehicles. The experiment will take place on a three-lane highway. Between the sessions, there will be a short break.

5.4.2 Controls

The vehicle in the driving simulator will have cruise control enabled from the start of the session. The car will accelerate from standstill to 100km/h on emergency lane of the highway and will maintain this velocity throughout the session (similar to a car with cruise control). Therefore, there is no need to use the gas pedal or brakes during the session.

Please, drive as you normally would and use the steering wheel for keeping the car in the lane, as well as for changing lanes when overtaking slower vehicles. Participants are urged to use the turn signal when changing lanes in both directions.

5.4.3 Scenario

During the experiment other road users will be driving on the road. You are asked to treat them as you would treat normal road users. The scenario consists of multiple driving situations on a highway in which overtaking a slow lead vehicle is desirable. You are asked to overtake this slow lead vehicle as you normally would, in a safe manner. You are asked to use the turn signals appropriately when changing lanes and to return to the right lane after overtaking.

Each driving session will start from standstill on the emergency lane on the right side of a three-lane highway. The car will accelerate to 100km/h on cruise control. You are asked to merge into the rightmost driving lane, when the car reaches a speed of 90 km/h, by changing one lane to the left (see figure 1). Note that other cars will be on the road as well .

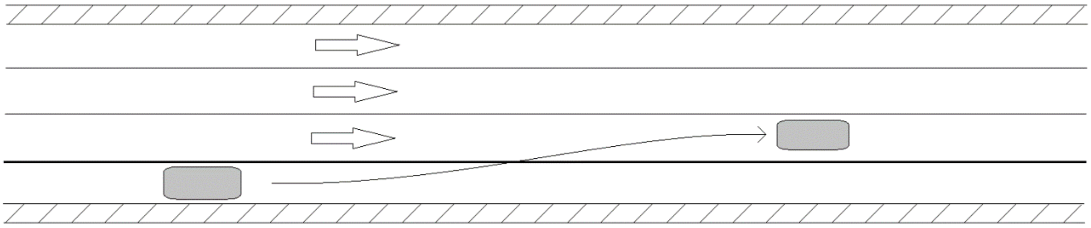

Figure 1: Figure 1 Merge into the rightmost lane

Now you are driving on the highway in the rightmost lane with a speed of 100km/h. During this session you will be asked to keep right unless overtaking a slow-moving vehicle, which is in line with the Dutch road safety laws.

When overtaking a slower lead vehicle, it is important to be aware of the vehicles around you and adjust your lane change accordingly. In other words, you are asked to change lanes as you normally would in such a situation, safely. However, remember that there are no speed controls (brakes, accelerator). Please, remember to use the turn signals appropriately.

5.5 Duration and time commitment

The experiment will take approximately 45 minutes and involves signing a consent form, practice simulator sessions, testing simulator sessions, breaks and completing questionnaires.

---

6 Expected benefits

It is not expected that the project directly benefits you. However, your participation in this study will add to our understanding of advanced driver assistance systems and the interaction with drivers. In this way your participation will assist in developing new approaches to improve driver safety and comfort.

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7 Risks associated with participation

Participants may experience simulator motion sickness. In case a participant experiences such sickness, the experiment can be stopped at any time. An emergency switch is available to the operator which will shut of the simulation immediately. Participants are instructed to wear their seatbelt during the entire simulation. The seatbelt can be unbuckled when the simulation has stopped and the operator has given permission to do so. Unbuckling of the seatbelt during simulation will shut down the simulation.

Taking place on the simulator requires you to climb up a small staircase, which might result in an accidental fall. The participant may only enter the simulator when the simulator is shutdown, to avoid tripping due to motion of the simulator. During the experiment, an operator ensures safe conduct of operation of the driving simulator. If the operator notices unsafe or unwanted behavior of the simulator or participant, the experiment may be terminated prematurely.

Losing control of the vehicle can result in a collision with the guard rail or other objects. The experience of a crash can be emotionally and physically demanding, as the motion base and visual screens simulate these collisions. Finally, other vehicles are non-solid objects, so a participant can drive through them. Riding through a non-solid object can be an emotionally uncomfortable experience.

8 Privacy and confidentiality

All comments and responses are anonymous and will be treated confidentially. The names of individual persons are not required in any of the responses. Publications or presentations of the results will not include any information that could identify you.

Any data collected as part of this project will be stored securely as per TU Delft's Research Data Management policy. Only the researchers involved in the project will have access to this information. Please note that non-identifiable data from this project may be used as comparative data in future projects or stored on an open access database for secondary analysis.

9 Sharing of results

Results of the study might be presented in scientific and driving simulator seminars and conferences, and published as PhD theses and articles in scientific journals. Data might also be used in related studies on driver behavior, training, training in simulators, design of vehicle safety systems, and human-machine interface design for vehicles.

10 Responsibility

The researchers, funding bodies or institutions involved do not bear any responsibility for possible inconveniences or damages during travel to or from the location of the experimental activity.

11 Questions/further information about the project

If you wish to ask questions about the project or require further information, please contact one of the researchers below:

Researcher	E-mail	Phone
Christiaan Koppel	C.N.Koppel@student.tudelft.nl	+31(0)6 1387 0623
Jelle van Doornik	J.vanDoornik@cruden.com	
David Abbink	D.A.Abbink@tudelft.nl	
Bastiaan Petermeijer	S.M.Petermeijer@tudelft.nl	

12 Ethical approval and complaints regarding the conduct of the project

This study has been approved by the Human Research Ethics Committee (HREC). If needed, verification of approval can be obtained either by writing to P.O. Box 5015, 2600 GA Delft, The Netherlands or by sending an email to HREC@tudelft.nl. If you do have any concerns or complaints about the ethical conduct of the project you may contact the HREC on the above mentioned addresses. The HREC is not connected with the research project and can facilitate a resolution to your concern in an impartial manner. Name of the experiment according to the Ethics Approval Application: *Haptic lane change guidance on a driving simulator*.

Consent Form for:

Lane change analysis on a motion base driving simulator

Please tick the appropriate boxes

Taking part in the study	**YES**	**NO**
I have read and understood the study information dated [Thursday 6th June, 2019], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
I understand that taking part in the study involves the logging of driving data. This study also involves the participant completing questionnaires.	☐	☐
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: motion sickness due to movement of the simulator. Physical and emotional discomfort due to the possibility of experiencing a collision scenario.	☐	☐
Use of the information in the study		
I understand that information I provide will be used for presentation in scientific and driving simulator seminars and conferences and published as Master's theses, PhD theses and articles in scientific journals.	☐	☐
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	☐	☐
Future use and reuse of the information by others		
I give permission for the driving simulator data that I provide to be archived in TU Delft repository so it can be used for future research and learning	☐	☐

Name of participant	Signature	Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Christiaan Koppel		
Name of researcher	Signature	Date

Appendix E

Questionnaire

Demographics questionnaire (June 2019)

Data for driving simulator experiment led by Christiaan Koppel. This data will be used for presentation in scientific and driving simulator seminars and conferences and published as Masterǒs theses, PhD theses and articles in scientific journals.

*Vereist

1. **Participant Number (ask experimenter)** *

   ____

2. **What is your age? (in years)** *

   ____

3. **What is your gender?** *

   Markeer slechts één ovaal.

   ○ Female
   ○ Male
   ○ Anders: ______________________

4. **How long do you have your driving license? (in years)** *

   ____

5. **How much do you drive yearly? (Last 12 months)** *

   Markeer slechts één ovaal.

   ○ 0-1.000 km
   ○ 1.000-5.000 km
   ○ 5.000-15.000 km
   ○ 15.000 km +

Appendix F

Results of questionnaire

Table F-1: Results of the demographics questionnaire which can be seen in Appendix E.

Participant	Age	Gender	In possession of driving license [years]	km driven in last 12 months
1	25	Male	7	5.000-15.000
2	40	Male	21	15.000 +
3	24	Male	3	15.000 +
4	23	Male	5	5.000-15.000
5	27	Male	7	1.000-5.000
6	29	Male	11	5.000-15.000
7	25	Male	7	0-1.000
8	24	Male	0.1	0-1.000
9	25	Male	6	1.000-5.000
10	30	Male	10	1.000-5.000
11	52	Male	32	5.000-15.000
12	22	Female	2	1.000-5.000
13	23	Male	4	1.000-5.000
14	23	Female	6	0-1.000
15	31	Male	15	15.000 +
16	38	Male	16	15.000 +
17	23	Male	3	5.000-15.000
18	22	Female	4	1.000-5.000
19	24	Male	6	5.000-15.000
20	25	Male	7	15.000 +
21	25	Female	7	0-1.000

Appendix G

Conference paper of pilot study

Lane change manoeuvre analysis: inter- and intra-driver variability in lane change behaviour

C.N.Koppel[1], S.M. Petermeijer[1], J. van Doornik[2] and D.A. Abbink[1]

(1) Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands, e-mail: {C.N.Koppel}@student.tudelft.nl, {S.M.Petermeijer, D.A.Abbink}@tudelft.nl
(2) Cruden B.V., Pedro de Medinalaan 25, 1086 XP Amsterdam, The Netherlands, e-mail: {J.vanDoornik}@cruden.com

Abstract - *In order to improve lane change assistance and automated lane changes, a better understanding of human lane change behaviour, in terms of trajectories and steering behaviour, is needed. This study focuses on quantifying inter- and intra-driver variability in lane change behaviour, in terms of lane change duration and steering behaviour. In an exploratory study, twelve participants drove 3 lane change scenarios in a moving base simulator study. The independent variable being the distance to a trailing vehicle in the target lane of 25, 35 and 50m. The results show that intra-driver variability is in the same range as inter-driver variability in terms of standard deviation: 1.6 and 1.1 seconds respectively for a mean lane change duration of 6.7 seconds. Variability between traffic scenarios is 0.57 seconds. Subsequent analysis showed that the lane change duration does not determine the steering behaviour during the lane change. Concluding, maximum and minimum steering angle as well as the integral of the steering angle could be useful metrics to describe lane change behaviour in addition to lane change duration. Furthermore, high intra-driver variability in lane change duration and steering behaviour requires adaptable trajectories that can accommodate the wide range of lane change behaviour. Additionally, a personalized initial lane change trajectory can be generated to mitigate inter-driver variability.*

Keywords: *lane change manoeuvre, driving simulator, haptic guidance, ADAS*

Introduction

Driving tasks are transferred from human to machine at an ever-increasing pace. These systems take over tasks previously performed by drivers, as illustrated by lane keeping assistance and adaptive cruise control. The focus of these systems is reducing workload and increasing comfort of drivers, in addition to increasing safety. Consequently, the need for an understanding of human driver behaviour arises, as highly automated vehicles are made to exhibit human-like driving behaviour in order to increase trust of drivers. In highway-driving, lane change manoeuvres are frequently executed and require the full attention of the driver. Therefore, assistance during lane changes would decrease workload and increase comfort of drivers.

In order to assist drivers during a lane change, a reference trajectory for the lane change is needed. Previous research on lane change trajectory generation in the field of haptic shared lane change guidance includes a system proposed by Tsoi [Tso10]; a system which generates a guidance trajectory based on the initial lateral velocity of the lane change. However, this assumes that all relevant variations in the lane change trajectory can be predicted by the initial lateral velocity. A different, adaptable approach is proposed by Cramer [Cra15]. In this approach, the lane change trajectory is adapted based on the driver input on the steering wheel during the lane change manoeuvre itself.

Research on the topic of driver behaviour and modelling during lane changes has focused mostly on gap acceptance [Dag81, Tol03] and lane change intent prediction [McC07, Sal04, Pen15] of drivers using the traffic situation, vehicle states and driver gaze measurements. However, less is known about the execution phase of the lane change. Research into the influences on the execution phase of the lane change has mostly been limited to the effects on the lane change duration for use in microscopic traffic flow simulation [Tol07, Cao13, Hil15]. Other studies used predictive algorithms to predict the lane change trajectory based on the lane change duration. Yao [Yao13] uses the k-nearest neighbours (k-NN) algorithm to predict the end point of the lane change, by interpolating previous lane change durations based on the traffic situation at the start of the lane change. Butakov [But15] used the traffic situation at the start of the lane change to predict the lane change duration based on personal previous lane changes in similar situations.

In the field of autonomous vehicles, lane change trajectory planning is viewed as an optimization problem. Optimal trajectories are generated that satisfy some safety constraints and minimize for example the maximum jerk or the total kinetic energy [Sha04]. These optimal trajectories might not be in accordance with human driving behaviour, leading to conflicts between driver and system and disuse of the automation [Par97]. Avoiding conflicts between automation and driver is especially important when control of the vehicle is shared between the automation and the driver [Abb12]. Conflicts in shared control lead to increased steering torques and a decreased acceptance of the system [Boi14].

So far, most trajectory generators use the lane change duration to characterize or predict the lane change trajectory. The duration is used to generate a standard kinematic or optimized trajectory between begin- and endpoint, such as a sine or polynomial. However, this assumes that the lane change duration determines both the steering behaviour and the trajectory of the lane change.

With lane change durations ranging from 2 seconds to 16 seconds [Tol07, Cho94], generating lane change trajectories is not straightforward. Two important factors that influence the duration of the lane change of drivers according to previous research are the traffic situation and the personal preference of the driver (inter-driver variability) [Tol07, Tom10, But15, Hil15]. The influence of the intra-driver variability, is not evident from literature. However, the relationship of inter- and intra-driver variability to the effect of the traffic situation plays a major role in determining a suitable method for generating lane change trajectories.

Therefore, an exploratory driving simulator study is conducted with the aim of quantifying the inter and intra-driver variability in lane change behaviour, with respect to the effect of the traffic scenario. More specifically, the aim is to answer the following questions. Firstly, does the lane change duration determine the steering behaviour during the lane change? And secondly, what is the effect of the traffic situation on the lane change characteristics, in terms of lane change duration and steering behaviour?

The remainder of this paper is structured as follows. Section 2 introduces the method and setup of the driving simulator experiment. Section 3 presents the results of the experiment. Sections 4 and 5 discuss the results and summarize the conclusions respectively.

Figure 1: The Cruden motion base driving simulator as used in the experiment with actuated steering wheel and 210 degrees projection screen with on-screen side- and rearview mirrors.

Method

Apparatus

The driving experiment was conducted on a six degrees of freedom (6-DOF) motion base simulator by Cruden, similar to the one used in the research of Willibald [Wil15]. The simulator consists of a hexapod providing vestibular and haptic feedback. Sway motion cueing was based on the lateral position, scaled with respect to the width of the three-lane highway with a factor of 0.125. The yaw motion was scaled equally and based on the vehicle heading [Moo19]. The visual environment was projected on a 210-degree projection screen using three projectors running at 120 Hz as seen in figure 1. Furthermore, the cockpit consisted of a driver seat, steering wheel with turn indicator, brake, and accelerator pedals. The force feedback on the steering wheel was provided by a control loader, with a maximum torque of 30 Nm, connected to a dedicated computer running at 1000 Hz. The Cruden Panthera internal car model was updated at 120 Hz, data was logged at 120 Hz. The integration of traffic into the simulation was done using VIRES virtual test drive software utilising the openDRIVE format.

Participants

A group of 12 participants (10 male, 2 female) participated in the experiment. The participants were recruited from within and outside the Cruden office. The participants had a mean age of 26 years (SD 3.7 years). All participants had normal or corrected to normal vision and were in possession of a valid driver license. Participation was on a voluntary basis and no compensation was offered.

Experiment design

The experiment was a within-subject design study in which the traffic situation was the within-subject factor. The participants completed 3 driving sessions; each driving session consisted of 10 different lane change scenarios in random order. Of these scenarios, 3 will be used in this research, resulting in a total of 9 lane changes per participant over 3 conditions (LC25, LC35, LC50), see table 1. The order of the driving sessions was counterbalanced according to the 3x3 Latin square in order to mitigate order effects. This resulted in a total of 9 lane changes per participant and a total of 36 lane changes per lane change scenario. The participants each drove a 4-minute practice session before the experiment on the three-lane endless highway in which they performed 10 lane change manoeuvres in order to get used to the workings of the driving simulator and the dynamics of the simulated vehicle. The driving experiment took place on a straight three-lane highway.

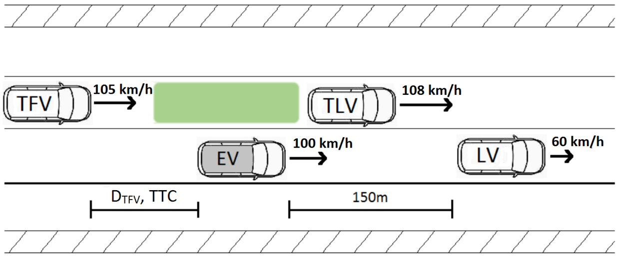

Figure 2: Generic scenario visualization: before the lane change is initiated, with independent variable D_{TFV} and time to collision (TTC) to TFV.

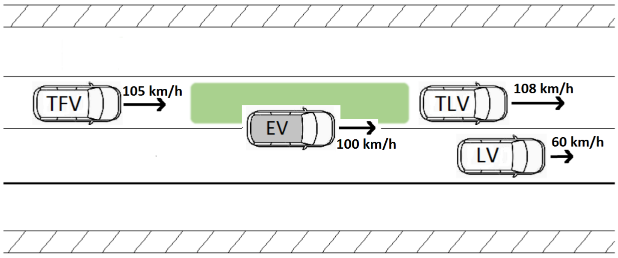

Figure 3: Generic scenario visualization: during the lane change, at the time of lane crossing.

Scenarios

The driving experiment took place on a straight three-lane endless highway. Each participant drove three sessions of 10 minutes each, in which they had to perform 10 different overtaking manoeuvres, totalling 30 overtaking manoeuvres per participant. Three of the ten different overtaking scenarios are used as data in the remainder of this research, resulting in 3 events per participant per scenario. In the scenario, 4 cars were of importance. The ego vehicle (EV), the target lead vehicle (TLV), the lead vehicle (LV) and the target following vehicle (TFV). The EV was driven by the participant with a fixed speed of 100 km/h, see figure 2. The LV, driving at 60 km/h was the vehicle that the EV had to overtake to maintain a speed of 100 km/h. Two other cars were present in front of the TLV and behind the TFV, there was no interaction between these cars and the EV.

When the LV is first visible, the target lane is occupied by 2 vehicles, of which the rear one is the target lead vehicle (TLV) driving at 100 km/h. Another two vehicles approach from behind in the target lane, of which the front one is the target following vehicle (TFV). The TLV and the TFV define the gap in the target lane as can be seen in figure 2 and 3. When the distance between EV and LV is 300 m, time to collision (TTC) is 27 seconds, the TLV starts accelerating from 100 km/h to 108 km/h. The TLV has eventually overtaken the EV when the distance between EV and LV is 150 m (see figure 2), creating the possibility for the EV to change lanes. Simultaneously, the TFV approaches in the target lane with a constant speed of 105 km/h. The gap in the target lane into which the EV will merge is now constrained by the TLV and TFV. When the longitudinal distance between TFV and EV becomes less than 15 m, the TFV will start decelerating to 99 km/h to avoid a collision with the EV.

Three different scenarios were created by varying the distance to the TFV (D_{TFV}). The TFV is driving at a distance of 25m, 35m or 50m measured at the time that the distance from EV to LV is 150 m (see figure 2). The 3 scenarios LC25, LC35 and LC50 can be seen in table 1. After the LV has been overtaken, a lane change back into the right lane is made in order for the following scenario to develop.

Instructions

Participants were instructed to keep in the right lane of the three-lane highway and to change lanes when needed to overtake slower vehicles. Participants were instructed to use the turn signal when changing lanes and were urged not to cross lane boundaries unless a lane change was being performed.

Table 1: Lane change scenarios (LC) with corresponding time to collision (TTC) and time headway (THW) between TFV and EV

Scenario	D_{TFV} [m]	TTC [s]	THW [s]
LC25	25	18	0.86
LC35	35	25	1.2
LC50	50	36	1.7

Lane change analysis

During the driving session the following signals were registered with a sample rate of 120Hz:

y	lateral position with respect to the road [m]
θ	steering wheel angle [deg]
D_{LV}	longitudinal distance of EV to LV [m]
D_{TLV}	longitudinal distance of EV to TLV [m]
D_{TFV}	longitudinal distance of EV to TFV [m]

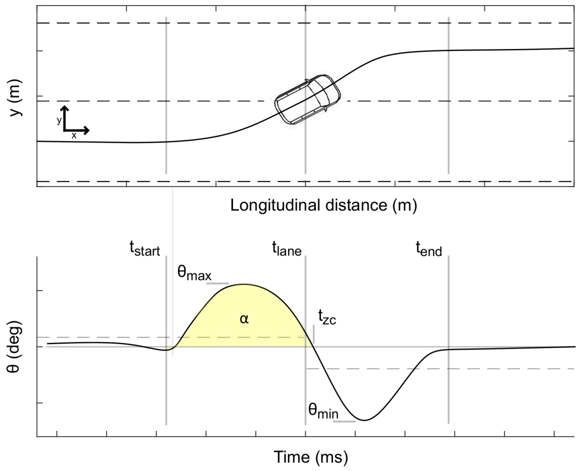

Figure 4: Lane change trajectory with corresponding steering wheel angle and visualization of the lane change duration and other characteristics.

The steering wheel angle θ was filtered with a fourth order low pass Butterworth filter with a cutoff frequency at 10Hz, to filter the noise above the human control bandwidth. The following characteristics were determined for each lane change manoeuvre (see figure 4).

Peak steering wheel angle left (θ_{max} [deg]). θ_{max} is the maximum value of the steering wheel angle to the left.

Peak steering wheel angle right (θ_{min} [deg]). θ_{min} is the minimum value of the steering wheel angle; the maximum steering wheel angle to the right.

Start of the lane change (t_{start} [s]). The start of the lane change is defined as: the last moment before the θ_{max} peak in which θ is smaller than one tenth of θ_{max} and $\dot{\theta}$ is smaller than 0.1 deg/s.

End of the lane change (t_{end} [s]). The end of the lane

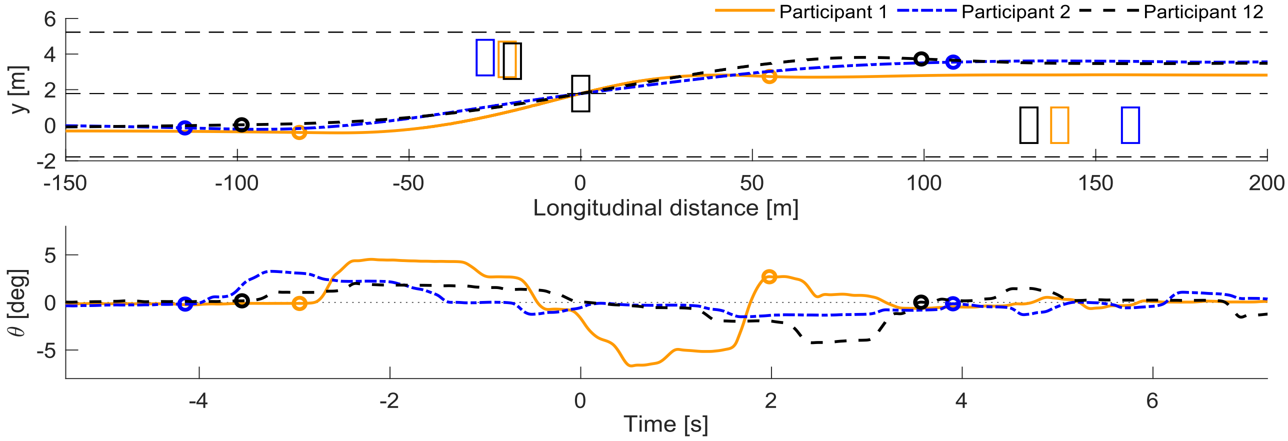

Figure 5: Scenario LC25 for three different participants, with start- and endpoints indicated. Positions of EV LV and TFV are shown at time t=0, when the EV crosses the lane boundary. Lane change durations for participant 1, 2 and 12 respectively: 4.9 s, 8.1 s and 7.1 s.

change is defined as: the first moment after θ_{min} in which θ is bigger than one fourth of θ_{min} and the $\dot{\theta}$ is smaller than 0.1 deg/s. Note that the θ threshold for the end of the lane change is less stringent than for the start of the lane change.

Lane crossing time (t_{lane} [s]). The half point of the lane change is defined as the moment at which the centre of gravity passes the lane boundary. This point in time t_{lane} is taken as $t = 0$ when analysing lane changes.

The end of the first steering peak (t_{zc} [s]). Defined as the point in time after θ_{max} where θ crosses zero.

Lane change duration (T_{lc} [s]). The total duration of the lane change from t_{start} to t_{end}.

Integral of steering wheel angle (α [deg s]). The integral of θ during the first half of the lane change, which could be seen as the amount of steering during the lane change.

Results

In figure 5, three lane change events can be seen by different participants as illustration for different lane change behaviour. Note that participant 1 has a relatively symmetrical lane change in which θ_{max} and θ_{min} are roughly equal and quite high. Participant 2 has a relatively high θ_{max} compared to θ_{min}, as opposed to participant 12, which has a low θ_{max} compared to θ_{min}.

Furthermore, a big difference in duration can be seen between participant 1 and the other 2. In part due to the lateral offset of participant 1 at the end of the lane change and partly due to the steering behaviour of participant 1.

Additionally, note that participant 2 and 12 achieve similar total steering α in the first half of the lane change and similar lane change duration, despite the differences in peak steering wheel angles.

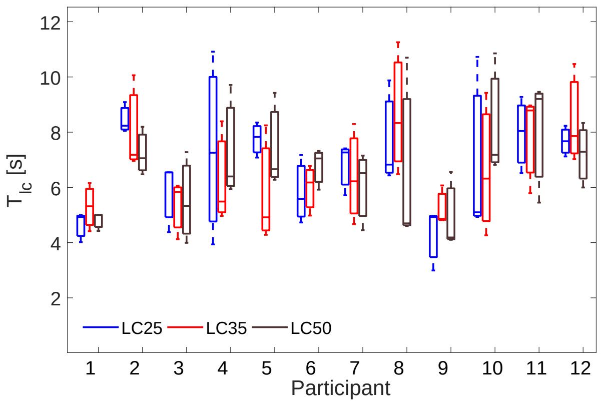

Figure 6: Lane change duration T_{lc} for LC25, LC35 and LC50 for all participants. Boxplot showing median, 75th percentile and minimum and maximum values.

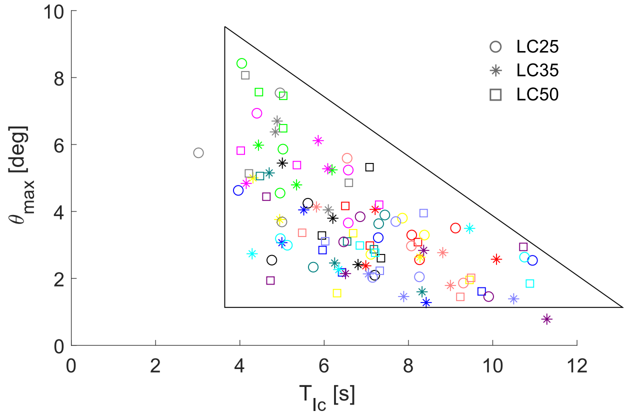

Figure 7: Lane change duration versus peak steering wheel angle per participant and lane change scenario LC25, LC35, LC50. Data of participants is grouped by colour. The triangle illustrates that high T_{lc} results in low θ_{max}, however low θ_{max} does not necessarily results in high T_{lc}.

Table 2: Descriptive statistics of the lane change characteristics for LC25, LC35 and LC50

	T_{lc} [s]	θ_{max} [deg]	$-\theta_{min}$ [deg]	α [deg s]
Range (minimum and maximum)	3.0-12	0.75-8.4	1.0-11	3.2-11
Mean	6.7	3.6	3.7	6.1
Range of the means	4.8-7.9	2.4-6.2	2.4-6.2	4.9-8.3
SD between participants	1.1	1.3	1.3	1.1
SD within the participant	1.6	1.1	1.2	1.2
Mean SD between scenarios	0.57	0.48	0.54	0.51

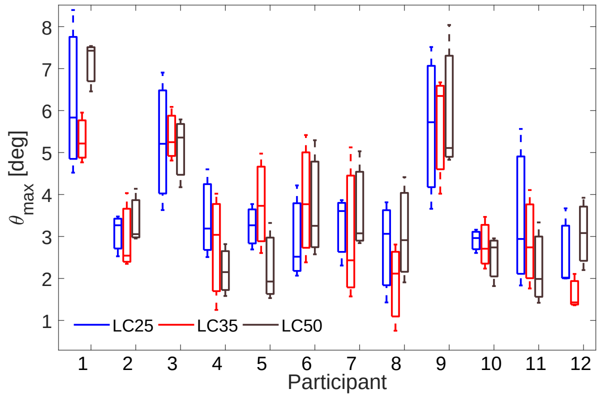

Figure 8: Peak steering wheel angle θ_{max} for scenario LC25, LC35 and LC50 for all participants. Boxplot showing median, 75th percentile and minimum and maximum values.

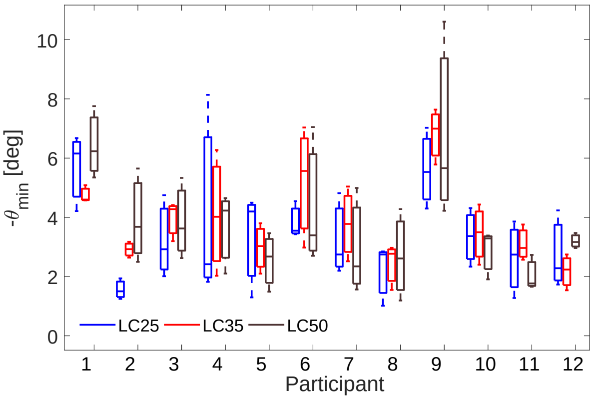

Figure 9: Peak steering wheel angle θ_{min} for scenario LC25, LC35 and LC50 for all participants. Boxplot showing median, 75th percentile and minimum and maximum values.

Lane change characteristics

Lane change duration T_{lc}

The lane change duration ranges from 3.0 s to 11s. Figure 6 shows there is a wide range of lane change durations. With a high variation both within and between participants. Looking between participants, the standard deviation (SD) of the means is 1.1 s. Looking within participants, the mean standard deviation per person per scenario is 1.6 s. Looking between scenarios, the mean standard deviation within a person between scenarios is 0.57 s as can be seen in table 2. The lane change duration does not explain all dynamics of a lane change. From figure 7 it can be seen that a high lane change duration (T_{lc}) coincides with a low peak steering wheel angle (θ_{max}). However, a low lane change duration (T_{lc}) does not necessarily mean that the peak steering wheel angle (θ_{max}) is high as well and vice versa. As an example, a T_{lc} of approximately 5 s could correspond with a θ_{max} between approximately 2 deg and 8 deg. Whereas a θ_{max} of approximately 2 deg could correspond with a T_{lc} between 4 s and 11 s.

Peak steering wheel angle θ_{max}

θ_{max} ranges from 0.75 deg to 8.4 deg as can be seen from figure 8. What stands out with respect to the lane change duration is that there is a relatively big difference between participants. Between participants, the standard deviation of the means is 1.3 deg. The mean standard deviation per person per scenario is 1.1 deg. Looking between scenarios, the mean standard deviation within a person between scenarios is 0.48 deg.

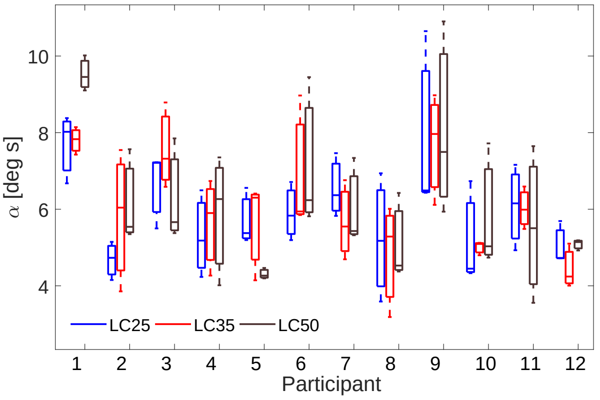

Figure 10: Integral of steering wheel angle α for scenario LC25, LC35 and LC50 for all participants. Boxplot showing median, 75th percentile and minimum and maximum values.

Peak steering wheel angle θ_{min}

θ_{min} ranges from -1.0 deg to -11 deg as can be seen from figure 9. Looking between participants, the standard deviation of the means is 1.3 deg. The mean standard deviation per person per scenario is 1.2 deg. Between scenarios, the mean standard deviation within a person between scenarios is 0.54 deg.

Integral of steering wheel angle α

α ranges from 3.2 deg s to 11 deg s as can be seen from figure 10. For the variability between participants, the standard deviation of the means is 1.1 deg s. Within participants, the mean standard deviation per person per scenario is 1.2 deg s. Between scenarios, the mean standard deviation within a person between scenarios is 0.51 deg s.

Inter- and intra-driver variability

As can be seen from figure 6 and table 2, there is a high variability in lane change duration. With mean T_{lc} per participant ranging from 4.8 s to 7.9 s with a standard deviation of the means of 1.1 s. The mean standard deviation within a person within a scenario is 1.6 s and the mean standard deviation within a person between scenarios is 0.57 s. This indicates that participants have a higher variation within the same scenario than they do between scenarios, or even between participants.

Looking at peak steering wheel angle θ_{max}, mean peak steering wheel angles per participant range from 2.4 deg to 6.2 deg. As opposed to lane change duration, the θ_{max} does have a higher variation between participants than within participants. The standard deviation of the means is 1.3 deg. Whereas the mean standard deviation within person within scenario is 1.1 deg. The mean standard deviation within a person between scenarios is 0.48 deg however. Again, this indicates a higher variation within and between participants than between scenarios.

Looking at peak steering wheel angle θ_{min}, mean peak steering wheel angles range from -2.4 deg to -6.4 deg. The standard deviation of the means is 1.3 deg. Whereas the mean standard deviation per person per scenario is 1.2 deg respectively. The mean standard deviation within a person between scenarios is 0.54 deg. This indicates that the inter-driver variability is similar to the intra-driver variability over all scenarios. Again, the standard deviation between scenarios is much lower than the inter- and intra-driver variability.

The area α, integral of the steering wheel angle during the first half of the lane change, has means per participant ranging from 4.9 deg s to 8.3 deg s. With standard deviation of the means between participants of 1.1 deg s. Mean standard deviation per person per lane change is 1.2 deg s. Between scenarios, the mean standard deviation per person is 0.51 deg s. This shows a lower variability between scenarios than within scenarios and between participants.

Discussion

Lane change analysis

When constructing human-like lane change trajectories, capturing lane change behaviour is paramount. In addition to lane change duration, this study investigated steering behaviour of the participants in different traffic scenarios. The goal was to determine whether lane change duration determines the steering behaviour during the lane change and to quantify the inter- and intra-participant variability in relation to the effect of the traffic scenario.

As can be seen from figure 2 the lane change duration (T_{lc}) ranges from 3 to 12 seconds. This is in line with other research reporting lane change durations between 2 and 16 seconds [Tol07], when taking into account the fixed speed of 100 km/h in this study, as well as the range of methods that is used in literature for determining start- and endpoints of lane changes.

Due to the constant velocity of the EV in this research, the lane change trajectory is a function of the steering behaviour. Therefore, this research focused on analysing steering behaviour. In literature, the lane change duration is assumed to determine the the steering behaviour and consequently the lane change trajectory. However, the results show that the lane change duration does not seem to be correlated with the other characteristics as illustrated by θ_{max} in figure 7.

The lane change duration (T_{lc}) is not a good indicator of human lane change behaviour. A range of steering characteristics is possible within one lane change duration, making the lane change duration a bad predictor for the steering input during a lane change manoeuvre.

Furthermore, the lane change duration is not easily measured. This is especially true for determining the end point of the lane change, since the transition from the end of the lane change to the start of lane keeping is not evident. This is corroborated by Toledo [Tol07] who found a large variety of methods for determining the beginning and ending of a lane change.

In order to capture the steering behaviour during the lane change execution, this study used the peak steering wheel angles θ_{max} and θ_{min} and the integral of the steering wheel angle α. These characteristics define the steering behaviour during the lane change in addition to the lane change duration. Future research should take into account steering behaviour and other metrics when analysing lane change behaviour. For example, context-based metrics that could be used to relate lane change behaviour to other traffic in a spatio-temporal context. This allows for a more detailed analysis of the lane change execution as opposed to the analysis of the lane change duration only.

Effect of the traffic scenario

Looking at the effect of the traffic scenario, what stands out is the relatively low variability that is explained by the traffic situation. For all characteristics, the intra-driver variability is higher than the inter-traffic variability. Although these results are limited to three traffic situations, it is still remarkable to find such a relatively high intra-driver variability.

Furthermore, there does not seem to be a correlation between TTC between EV and TFV and any of the lane change characteristics. This is illustrated by the lack of a trend in the lane change scenarios in figures 6, 8, 9 and 10. The effect of LC25, LC35, and LC50 on the lane change characteristics can thus be neglected for this research.

Additionally, the inter- and intra-driver variability are in the same order of magnitude. This gives the impression that, although drivers are different from one another on average, they cannot be discriminated easily due to the high intra-driver variability. Additionally, high intra-driver variability indicates that participants are very inconsistent in the same traffic scenario.

Trajectory generation

When creating human-like lane change trajectories for automated lane changes or lane change assistance systems, two approaches of adapting to the current lane change trajectory can be discriminated. The adaptable approach gives the human the control and the responsibility to adapt the automation to the situation as desired. The adaptive approach on the other hand adapts to external factors such as the traffic situation.

Due to the high intra-driver variability over all characteristics that is exhibited by the participants in this study, an adaptable approach such as Cramer proposed [Cra15] would be preferred. Such an adaptable system would allow for the high variability in lane change duration and steering behaviour to be accommodated regardless of the cause of the variability. However, this has a downside too; the driver always has to adapt the system in order to fit his/her needs.

An adaptive system on the other hand could be used to create a personalized trajectory, based on average personal lane change behaviour. This personalized trajectory could be used as initial trajectory to be adapted by the adaptable system. This would benefit drivers with more extreme driving behaviour, without losing the flexibility of the adaptable system.

In addition, it is shown that people drive differently when driving with assistance systems than when driving manually [Mad18]. This complicates the conception of personalized trajectories. It also begs the need for research into the acceptance of human-like lane changes in autonomous vehicles and lane change assistance systems.

Limitations

The fixed speed of the ego vehicle did accommodate the possibility to create reproducible scenarios. However, this eliminated the possibility to accelerate during the lane change, excluding an integral part of lane changing behaviour. Furthermore, the other road users were pre-programmed, which removed the possibility of interaction or negotiation with the other road users.

As stated in the results, only three traffic scenarios, LC25, LC35 and LC50 are used. These scenarios provide a range of time to collisions between the ego vehicle and the approaching vehicle of 18 s to 36 s. The distance and TTC to the slower lead vehicle are intentionally quite high and non-critical to be able to find an effect of the different TTCs between EV and TFV. However, this might have affected the lane change intention and timing of the lane changes of the participants.

Furthermore, only three traffic scenarios are investigated in this research, showing little effect. However, other more extreme scenarios could be thought of in which the traffic situation might have more effect on the lane change behaviour of drivers. In addition, only 3 repetitions per participant per scenario are done, which limits the statistical substantiation.

Conclusion

In this study, the lane change duration and steering behaviour during a lane change have been studied from a viewpoint of inter- and intra-driver variability and the effect of traffic scenarios. Previous studies showed little data on steering behaviour and consequent lane change trajectories. However, in order to design human-like lane change trajectories for assistance systems, information about steering behaviour is needed in addition to lane change duration. For example, the information about steering behaviour in terms of maximum steering wheel angles and total amount of steering could be used.

Both the inter- and intra-driver variability exceed the effect of the traffic situation for the investigated scenarios. The low spatial and temporal criticality of the scenarios allows for high variability in lane change duration and steering behaviour. Due to the high intra-driver variability, creating adaptable lane change trajectories is the preferred method for accommodating the wide range of human lane change trajectories. In addition, an adaptive system could create personalized lane change trajectories that can be used as an initial trajectory for the adaptable system.

Future work which examines the steering behaviour in more detail is needed. The aim should be to find discriminatory characteristics on which a personalized trajectory can be based. A promising metric seems to be the maximum steering wheel angle which shows the highest inter-driver variability. Furthermore, spatio-temporal context of the lane change behaviour should be investigated, with the aim of finding relations between lane change behaviour, lane change timing and traffic situation. Lastly, human-like lane change trajectories should be implemented and tested in lane change support systems in order to assess whether individualized lane change assistance systems indeed increase acceptance by drivers.

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