

Driving behaviour at traffic light intersections

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Abstract

To develop a driver assistance system with the goal to increase driving efficiency, we aimed at understanding unassisted driving behaviour. With this knowledge we will then be able to estimate the potential of the assistance system to support drivers in avoiding unnecessary deceleration and acceleration when approaching traffic lights and to estimate the amount of influence the driver assistance system could have on normal driving. Efficient driving was defined as driving behaviour that leads to reduced fuel consumption and emissions.

In a driving simulator experiment with twelve participants and a within-subjects design drivers approached intersections while the traffic light was either solid green or solid red, or changed from red to green or from green to red during the approach. In addition, we varied whether there was a lead vehicle present and manipulated visibility through the presence or absence of fog. Driving speed, acceleration and pedal usage were analysed and interpreted due to their relation with fuel consumptions and emissions, which is well known from the literature.

Participants avoided strong accelerations and decelerations when approaching a solid green traffic light compared to a changing red to green traffic light. Speed was reduced earlier, when the traffic light was solid red compared to when the traffic light changed from green to red. Higher visibility in the non-fog conditions compared to the fog condition was only an advantage in terms of more efficient driving behaviour when the traffic light phase did not change during the approach. The potential for improvements in driving efficiency was higher when drivers were in free driving compared to when following a lead vehicle. We propose that approaching traffic light intersections takes place in three phases: an orientation, a preparation and a realisation phase. A driver assistance system is expected to improve drivers' anticipation of the driving scene and could recommend efficient driving behaviour in all three phases.

1 Introduction

There has been an increasing interest in improving driving efficiency in terms of throughput, traffic fluency and waiting times, and in reducing fuel consumptions, emissions and noise when approaching traffic light intersections (e.g. Barbé & Guy, 2008; Bley, et al., 2011; Kamal, Mukai, Murata, & Kawabe, 2010). In the following, efficiency relates to driving behaviour that leads to low fuel consumption and reduced emissions. Fuel consumption and emissions have been shown to be influenced by driving speed and acceleration (Ericsson, 2001; Rittger & Schmitz, 2013; van der Voort, Dougherty, & van Maarseveen, 2001; Van Mierlo, Maggetto, Van de Burgwal, & Gense, 2004). Therefore, we assume that avoiding strong accelerations and decelerations and smoothening speed profiles will increase driving efficiency by reducing fuel consumptions and emissions.

Traffic light intersections are an inevitable component of urban traffic. However, due to the frequently occurring accelerations, decelerations and speed variations at the intersections, they contribute largely to the efficiency of urban driving. To increase efficiency when driving at traffic light intersections, different approaches have been considered. For example, there have been global strategies such as controlling traffic lights on demand to avoid stops (e.g., Gradinescu, Gorgorin, Diaconescu, Cristea, & Iftode, 2007; Khakhutskyy, 2011) or investments of car manufacturers in improving engine and car body properties for example by introducing stop/start systems (e.g., Tamai, Hoang, Taylor, Skaggs, & Downs, 2001). Moreover there have been attempts to influence individual driving styles by driver assistance and information systems (e.g., Krause, Rommerskirchen, & Bengler, 2012). Wue, Zhao and Ou (2011) showed that with a driver assistance system influencing acceleration and deceleration behaviour at traffic light intersections up to 31% fuel savings could be achieved in specific situations.

Yet, in order to estimate whether and to which extent driver assistance systems can improve efficiency when approaching traffic lights, we first need to know how drivers approach traffic lights in driving situations without assistance systems. This is the focus of the present study.

The observation of driving behaviour in specific scenarios and situations is an important tool of transportation research (Liu, 2006). When we aim at supporting the driver with in-vehicle driver assistance systems, we need to know the unassisted driving behaviour (Berndt, Wender, & Dietmayer, 2007). In particular, in-depth knowledge of the driving behaviour when approaching traffic light intersection allows for two conclusions. First, it allows estimating the potential of interventions in driving behaviour with respect to efficiency. The goal is to identify the parameters of situations influencing efficient or non-efficient driving behaviour. Second, driver assistance systems usually change the cognitive and psycho-motoric tasks that drivers perform (Fastenmeier & Gstalter, 2008).

Information about unassisted driving behaviour allows estimating the extent of differences between normal and adapted driving behaviour. Thus, the analysis of the potential benefits of specific situations on efficiency together with the estimations of the magnitude of impact of the assistance system on normal driving behaviour represents a necessary justification for its development.

Previous research involving driving behaviour when approaching traffic lights has mainly focused on the specific situation when the traffic light changed from green to red during the approach. Recommendations for the design of traffic light timings have been given based on the relation between amber phase onset timing and deceleration behaviour. For example, El-Shawarby, Rakha, Inman, and Davis (2007) varied the onset of the amber phase on a controlled field track. Results showed that deceleration increased from -2.2 m/s^2 to -5.9 m/s^2 for the amber phase onsets from 5.6 s to 1.6 s before the stop line when approaching with 72 km/h.

The decision to proceed or to stop has been formulated as the dilemma zone problem, that initially was defined as a binary decision problem (Gazis, Herman, & Maradudin, 1960) in which the driver has to decide between two conflicting action alternatives. More recently, a transitional zone has been defined at amber onset as the zone when drivers are in the condition of having to decide whether to proceed or to stop (Goh & Wong, 2004). Other researchers defined the dilemma zone as the area in which neither safe stopping nor proceeding before the red signal is possible (Newton, Mussa, Sadalla, Burns, & Matthias, 1997). It has been reported that the uncertainty experienced when approaching traffic light intersections is associated with a certain degree of anxiety (Kikuchi, Perincherry, Chakroborty, & Takahashi, 1993) and increased workload (Kaul & Baumann, 2013) that can result in a workload compensation by reducing speed while approaching the intersection (Harms, 1991; Rataj & Vollrath, 2006). Drivers also subjectively rated traffic light intersections as being more strenuous than non-signalised intersections (Rataj & Vollrath, 2006). Conflicts with other road users might occur, because different drivers come to different decisions on how to approach the current phase (Liu, 2006).

In the present study, three main factors relevant for driving at traffic light intersections were varied: Traffic light phasing, the presence of a lead vehicle and visibility. We hypothesise that the introduced factors help to identify the parameters of situations in which a traffic light assistant could be beneficial.

Traffic light intersections differ from intersections with other traffic signs. The traffic light phases indicate alternating right of way rules that can change unexpectedly. There are four different relevant approaching scenarios at typical German traffic light intersections. (1) Approaching a traffic light that remains green requires proceeding. (2) Approaching a traffic light that remains red requires stopping. (3) Approaching a green light that changes to amber and subsequently to red requires preparation for stopping (i.e., for a loss of right of way). (4) Approaching a red light that changes to amber combined with red and subsequently to green requires preparing for proceeding

after the red phase. Changing traffic light phases imply changes in the right of way rules. With that, the anticipation of the traffic light status at arrival at the intersection might not be accurate. Traffic light phase transitions change the required driving behaviour while their timing can frequently not be anticipated correctly. Therefore, considering all possible traffic light phases when investigating driving behaviour is crucial.

In various other traffic situations, anticipation was identified as major influence on driving behaviour. Researchers have pointed out that the correct anticipation of the traffic situation is crucial to implement an efficient driving style (Arama, Balos, & Mosoiu, 2010). For example, Popiv, Rommerskirchen, Rakic, Duschl, and Bengler (2010) showed that by increasing drivers' anticipation of the development of the upcoming traffic scenario (e.g., parking cars or stagnant traffic on a highway) by a driver assistance system, fuel consumption was reduced. We hypothesise that because the traffic light phases change during the approach of an intersection, anticipation of the traffic light status might not be correct. Hence, drivers apply decelerations or accelerations that are not appropriate for the next traffic light phase but might have been appropriate for the current traffic light phase. Consequently, accelerations and decelerations are expected to be stronger when the traffic light phase changes compared to when the traffic light phase is solid. Additionally, the research on the dilemma zone problem showed that a driver assistance system might have the potential to reduce the uncertainty drivers can experience when making the decision to stop or proceed at the intersection.

Moreover, researchers have demonstrated the influence of lead vehicles on driving behaviour at intersections. For example, in a controlled field test setting, El-Shawarby, Rakha, Amer, and McGhee (2011) introduced other road users in the scene. Occasionally, a lead or a following vehicle appeared. In 50% of the trials, the traffic light remained green, whereas in the other 50% of the trials the lights changed from green to amber/red. Participants either drove with a speed of 72.4 km/h or 88.5 km/h. When the traffic light changed from green to red, drivers showed stronger decelerations when following a vehicle that legally proceeded through the traffic light compared to a single approach. No difference in deceleration occurred when drivers approached with a vehicle following them compared to traffic light approaches without any following or leading vehicle. Thus, only lead vehicles had an impact on driving behaviour when approaching traffic lights that change from green to red.

Further, a lead car seemed to reduce driving task difficulty. Kaul and Baumann (2013) investigated cognitive load by means of pupil dilation as an indicator for workload when approaching traffic light intersections at amber onset in a driving simulator study. When there was a lead vehicle, drivers showed better performance in a secondary task while approaching, and there was a tendency for more pupil dilation without lead vehicle compared to driving with lead vehicle. Increased pupil dilation represents increased workload. The authors concluded that following a lead car might be performed based on bottom-up processes. Therefore, approaching the traffic light

with lead vehicle requires less cognitive resources compared to single approaches. If driving behaviour is influenced by the presence of a lead vehicle, the potential for improvements in driving efficiency might also vary according to driving with or without vehicle ahead. Consequently, conclusions for adaptations of the parameters of a driver assistance system might be reasonable based on the current traffic condition.

Finally, there have been reports on the influence of visibility of the intersection scenario on difficulty of driving through the intersection. For example, Rataj and Vollrath (2006) varied visibility in their driving simulator study by placing between zero and four buildings at the edges of non-signalised intersections. The researchers found that when the view of the upcoming intersection was blocked, the time drivers needed to pass the intersection increased. This was interpreted as an increase in difficulty. Werneke, Kassner, and Vollrath (2008) reported fog as a negative visibility condition for which drivers require support by driver assistance systems in order to reduce strain.

When visibility conditions are good, drivers can identify the traffic light earlier during the approach than in bad visibility conditions. Caird, Chisholm, and Lockhart (2008) showed an influence of visual information about the presence of an upcoming traffic light on the stopping decisions of drivers at very short amber light onsets. Drivers reduced their speed when approaching the intersection after receiving the information from the in-vehicle sign that showed that a traffic light was ahead. Hence, merely knowing that there is a traffic light led to more anticipative driving. Contrary, Goh and Wong (2004) reported that drivers see a traffic light change to red, but feel no need for a reaction towards it, when the distance at light change is sufficiently large. In the present study, early vs. late visibility of the traffic light was realised by the introduction of fog. We hypothesise that decreasing drivers' foresight to the traffic light changes driving behaviour towards less efficient driving in those situations, in which early adaptation of driving speed is appropriate. In turn, in situations in which early adaptations are less beneficial for efficiency (e.g., when the traffic light changes), the increased foresight should reduce efficiency of driving. With that we could show the potential and limitations for a driver assistance system supporting the driver with early information on the presence of a traffic light.

In summary, the goal of the present study was to increase the knowledge on driving behaviour when approaching traffic light intersections. Results should be interpreted in terms of the potential of a driver assistance system to increase efficiency when approaching traffic light intersections. Thereby, we measured driving speed and acceleration and deceleration behaviour as indicators for driving efficiency with assuming that low accelerations and decelerations and smooth speed profiles are related to lower fuel consumptions and emissions. We assessed the impact of different traffic light phases, the presence of a lead vehicle and visibility conditions. All factors were varied within a controlled driving simulator setting. In the following sections, the methods of the

experiment are explained, the results are discussed and implications for the development of the driver assistance system are given.

2 Material and Methods

2.1 Participants

Twelve (four female) participants took part in the study. They were paid for their participation. The mean age was 26.8 (sd = 6.6) years. The mean self-reported annual driving experience was 13775 km (sd = 9344.8), with roughly 37.5% (sd = 22.3) experienced in urban environments. Participants were recruited from the WIVW GmbH (Würzburg Institute for Traffic Sciences) test driver panel. Therefore, they were well trained for driving in the static driving simulator. All drivers had normal or corrected to normal vision. No driver was colour blind.

2.2 Apparatus

The study took place in the static driving simulator of WIVW GmbH. The simulator had a 300° horizontal field of vision, with five image channels, each one with a resolution of 1024x768 pixels. In addition, there were two LCD displays representing the rear view mirror and the left outside mirror and one LCD display for depicting the speedometer. Auditory output in terms of vehicle motor sound was presented by a 5.1 Dolby Surround System. Overall there were nine PCs (Intel Core 2 Duo, 3 GHz, 4 GB Ram, NVidia GeForce GTS 250) connected via 100 Mbit Ethernet. The update frequency was 120 Hz. The driving simulation software SILAB was used. During the procedure the experimenter observed all driver views on separate display screens and communicated with the participants via intercom.

2.3 Design

The study had a within-subjects design. The factors traffic light phase, lead vehicle and fog were varied. The four different traffic light phases were either solid green or solid red, or changed during the approach from red to green or from green to red. There was either a lead vehicle during the approach or no lead vehicle. Visibility was manipulated by presenting fog, so that in parts of the traffic light approaches the distance at which drivers were able to see the traffic light was reduced. The order of the factor combinations (traffic light phase, fog, and vehicle) was randomised within the test track. The order was the same for all participants. To increase validity of data, each condition was presented more than once to every driver. In order to limit the duration of the experiment, the fog conditions were repeated twice, whereas the non-fog conditions were presented three times. Hence, every driver approached a total of 40 intersections. Additionally, the influence of distance to the traffic light was

investigated based on 23 distance segments, which divided the traffic light approach from 230 to 10 m in front of the intersection into 23 sections.

The dependent variables were speed, maximum acceleration and maximum deceleration. Pedal usage was investigated in terms of the occurrence of accelerator pedal release and brake pedal onset. Drivers actively control speed and pedal usage and recommendations given by the driver assistance system can directly influence speed choice and pedal usage. As mentioned before, acceleration and deceleration strongly relate to efficiency and therefore indicate the potential of the driver assistance system for increases in driving efficiency.

2.4 Test track

The test track consisted of an urban environment, with 40 intersections with the same X-junction layout but varying environmental design (buildings, landmarks, plants). Overall, the track was approximately 25 km long, with approximately 600 m between two traffic light intersections. Driving through the test track once took approximately 40 minutes. In the intersection areas, there were three lanes: one single lane for turning left, one single lane for driving straight, and one single lane for turning right (Figure 1). The traffic light phasing for the three lanes did not differ. Participants as well as the lead vehicles always drove on the middle lane. There was no other traffic than the lead vehicle, which allowed us to control for cues about the right of way rules that could be obtained from other road users in the intersection area.



Fig. 1 Screenshots of the test track with lead vehicle (upper left and bottom left) and fog (upper left and upper right)

The lead vehicle appeared in front of the drivers at a distance of 300 m in front of the intersection and drove with a speed of 46.8 km/h (13 m/s). The lead vehicle always drove according to the traffic rules. When the traffic light changed from red to green, the lead vehicle proceeded. When the traffic light changed from green to red, the lead vehicle stopped. The lead vehicle started decelerating towards the solid red light or the changing green

to red light at around 72 m in front of the intersection with around -3 m/s^2 , which is considered as normal driving behaviour (El-Shawarby et al., 2007). The mean distance drivers chose to follow the lead vehicle was 29.7 m (sd = 2.1 m). After crossing the intersection, the lead vehicle accelerated and left the driving scene.

Before the main experiment started, a pre-test was conducted. Every participant approached the traffic light intersection with and without fog. They were instructed to press a button at the steering wheel at the moment they could see the traffic light. The average distance at which participants saw the traffic light was 182.3 m in front of the intersection when there was no fog and the maximum distance at which a driver could see the traffic light was measured at 230 m in front of the intersection. With fog, visibility reduced to an average of 90.9 m in front of the intersection with a maximum of 110 m.

The traffic light phasing followed the German road traffic regulations (Wissmann & Merkel, 1998). The red phase always ended with a combined presentation of red and amber light, whereas the green phase ended with an only amber state. The amber phase lasted approximately 1.8 s and the combined red and amber phases lasted approximately 1.2 seconds. The red phase following the single amber state lasted for 16 s. The traffic light phase changes occurred 80 m in front of the intersection in all conditions in order to standardise conditions. This distance allowed for sufficient time to either avoid a stop at red in case of the change to green and to appropriately initiate a stop at red in case of a change from green to red. No participant crossed the intersection at a red light.

2.5 Procedure

Participants received instructions about the objectives of the study. They learned that driving behaviour at traffic light intersections was investigated. Subsequently, they filled out a data privacy statement. They were familiarised with the test setting and the test track by driving a short practice track consisting of six traffic light intersections with a combination of different traffic light phases, lead vehicle and fog conditions. For the main part of the experiment participants were instructed to strictly follow the traffic rules. Overall, the procedure lasted on approximately one hour.

3 Results

Before data analysis, we investigated the correlation between time during the experiment and the dependent variables speed, acceleration and deceleration. Results indicated that there were no learning effects for the conditions. Additionally, we investigated differences in mean driving speed between the repetitions of each factor combination and determined if differences occurred between similar traffic light approaches depending on the different preceding experimental conditions. No order effects were detected.

For the analyses, data were averaged over repeated traffic light intersection approaches for each participant. The analyses of variance (ANOVAs) were conducted according to the repeated measurements design. We included data for the area of 230 m in front of the intersection, because this represented the maximum distance that participants expressed to be able to see the traffic light state. The analyses were conducted separately for traffic light approaches without a stop (i.e., green and red to green traffic light phases) and traffic light approaches with a stop (i.e., red and green to red traffic light phase).

3.1 Speed

For the analysis of speed profiles when approaching the traffic lights, we considered the mean speed in 10-meter segments, starting at 230 m and ending 10 m in front of the intersection. The respective distance sections will be referred to by the upper boarder of the segment (e.g., 230 for the distance segment 230 – 220 m in front of the intersection).

First, we investigated speed profiles for traffic light approaches without a stop. Figure 2 shows that drivers adapted their speed over the course of the traffic light approach when the traffic light changed from red to green. Changes in driving speed were low, when the traffic light was solid green, and when there was fog in the track in the red to green condition.

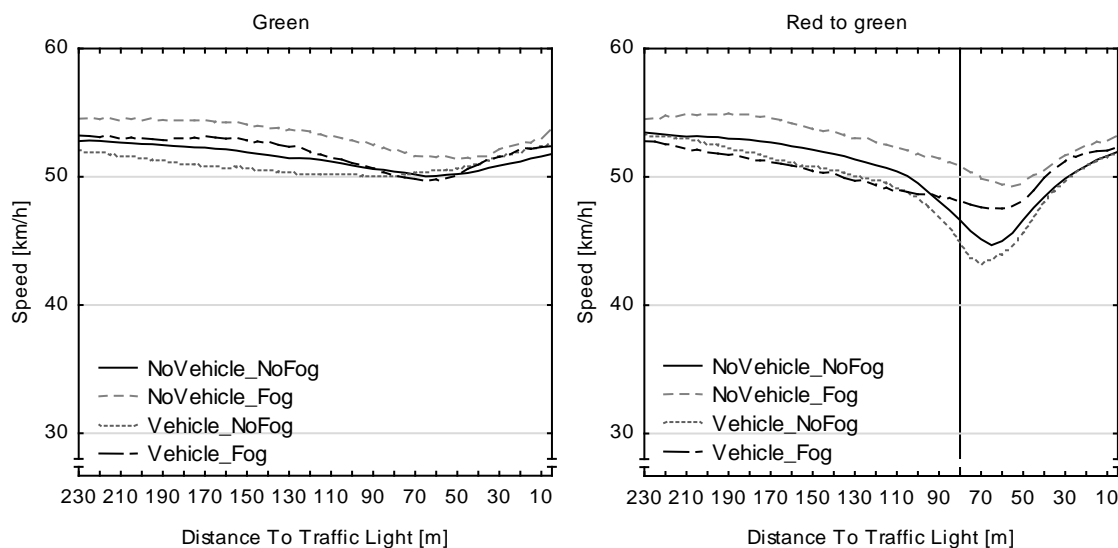


Fig. 2 Mean speed profiles for the different lead vehicle and fog conditions for the green (left) and the changing red to green (right) traffic light phase. The vertical black line indicates the distance at which the traffic light phase change occurred

Separate ANOVAs for each single distance section were conducted. The independent variables for the 23 ANOVAs were traffic light phase, lead vehicle and fog, respectively. The alpha level was Bonferroni adjusted to .0011, because overall we conducted 46 separate ANOVAs, 23 for the comparison of green and red to green lights and 23 for the comparison for red and green to red lights (see below). Results for the green and red to green lights

are presented in Table 1. Driving speed differed between the traffic light phases solid green and red to green in the distance sections 120 – 50 m in front of the intersection. Participants drove faster when the traffic light was solid green compared to changing red to green. Without lead vehicle driving speed was higher between 120 – 110 m in front of the intersection. Fog influenced driving speed especially between 80 – 70 m in front of the intersection, with higher driving speeds when fog was present compared to no present. No other effects in any other distance section were significant.

Table 1 ANOVA results (*p*-values) for each distance section of 10 m with the dependent variable driving speed. The factor traffic light phase distinguishes between solid green and changing red to green traffic lights. The alpha level was Bonferroni corrected with considering that 46 ANOVAs were conducted at the same data material. Bold numbers indicate significant effects. TLP = traffic light phase, LV = lead vehicle, F = fog

Effect	230-140	130	120	110	100	90	80	70	60	50	40-10
TLP	all <i>ps</i> >.007	.002	.001	.001	<.001	<.001	<.001	<.001	<.001	<.001	all <i>ps</i> >.089
LV	all <i>ps</i> >.002	.001	.001	.001	.001	.003	.010	.026	.068	.283	all <i>ps</i> >.703
F	all <i>ps</i> >.011	.027	.025	.016	.005	.003	.001	<.001	.011	.094	all <i>ps</i> >.143
TLP x LV	all <i>ps</i> >.114	.127	.116	.096	.135	.194	.183	.243	.327	.384	all <i>ps</i> >.470
TLP x F	all <i>ps</i> >.003	.042	.138	.473	.598	.074	.010	.004	.008	.070	all <i>ps</i> >.156
LV x F	all <i>ps</i> >.076	.078	.044	.019	.005	.005	.014	.020	.075	.250	all <i>ps</i> >.206
TLP x LV x F	all <i>ps</i> >.105	.223	.251	.363	.571	.902	.387	.340	.328	.485	all <i>ps</i> >.579

Second, we investigated driving speed during traffic light approaches with a stop (Figure 3). Driving speed differed between the distance sections, because drivers reduced speed to initiate the stop over the course of the approach.

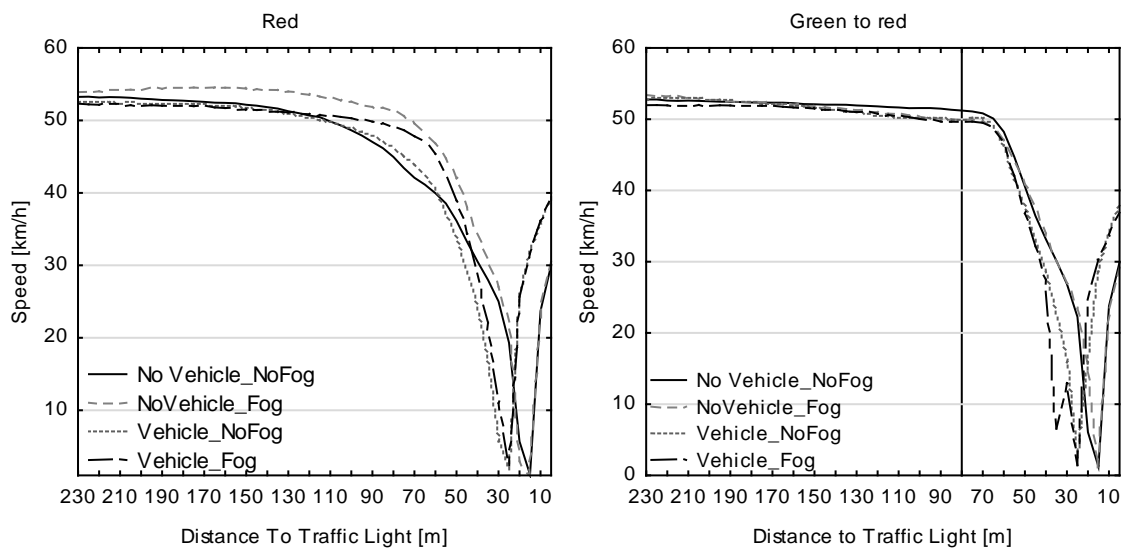


Fig. 3 Mean speed profiles for the different lead vehicle and fog conditions for the red (left) and the changing green to red (right) traffic light phase. The vertical black line indicates the distance at which the traffic light phase change occurred

Table 2 contains the results of the 23 ANOVAs conducted separately for each distance section with the factors traffic light phase, lead vehicle and fog. As mentioned before, the alpha level was Bonferroni adjusted to .0011. Importantly, speed differed significantly between approaches of solid and changing traffic light in the distance sections 90 – 70 m in front of the intersection. This was the area in which drivers started preparing for a stop when approaching a solid red traffic light while when approaching a changing green to red traffic light drivers' initiation of the stop was delayed. Trivially, drivers stopped at a larger distance to the traffic light when there was a lead vehicle ahead, which explains the significant influence of lead vehicle in the distance sections smaller than 50 m in front of the intersection. The significant interaction between traffic light phase and fog in the distance section 110 to 50 m shows that fog influenced the initiation of the stop at the red light only in the solid red condition but not in the changing green to red condition.

Table 2 ANOVA results (p -values) for each distance section of 10 m with the dependent variable driving speed. The factor traffic light phase distinguishes between solid red and changing green to red traffic lights. The alpha level was Bonferroni corrected with considering that 46 ANOVAs were conducted at the same data material. Bold numbers indicate significant effects. TLP = traffic light phase, LV = lead vehicle, F = fog

Effect	230-120	110	100	90	80	70	60	50	40	30	20	10
TLP	all $ps >.013$	.742	.076	.001	<.001	<.001	.001	.153	.102	.158	.017	.138
LV	all $ps >.005$	.008	.022	.072	.264	.252	.001	<.001	<.001	<.001	<.001	<.001
F	all $ps >.246$	.186	.120	.039	.006	.010	.013	.004	.188	.292	.045	.880
TLP x LV	all $ps >.040$	.654	.965	.966	.864	.949	.555	.463	.047	.077	.302	.258
TLP x F	all $ps >.005$	.001	<.001	<.001	<.001	<.001	<.001	.001	.064	.340	.830	.249
LV x F	all $ps >.107$	.267	.187	.082	.035	.433	.855	.764	.220	.943	.629	.465
TLP x LV x F	all $ps >.028$	.012	.006	.007	.018	.043	.466	.240	.495	.668	.017	.836

3.2 Acceleration and deceleration

We separately considered maximum accelerations and maximum decelerations. For maximum accelerations in conditions in which drivers were able to pass the intersection without a stop (i.e., green and red to green phase), an ANOVA with the factors traffic light phase, lead vehicle and fog was conducted. There were significant main effects for the factors traffic light phase, $F(1,11) = 17.691, p = .001, \eta^2_{\text{partial}} = .617$, and fog, $F(1,11) = 5.500, p = .039, \eta^2_{\text{partial}} = .333$. Maximum acceleration was larger when the traffic light phase changed from red to green and when there was no fog in the track. Additionally, the interaction between traffic light phase and fog indicated that when drivers approached the solid green traffic light, there was no difference between conditions with fog and without fog, $F(1,11) = 7.587, p = .019, \eta^2_{\text{partial}} = .408$. When the traffic light changed from red to

green, maximum acceleration was larger when there was no fog in the track compared to approaches with fog (Figure 4, left).

In a subsequent ANOVA we investigated maximum deceleration for approaches without a stop. For green and red to green traffic lights, the main effects traffic light phase, $F(1,11) = 18.102$, $p = .001$, $\eta^2_{\text{partial}} = .622$, and fog, $F(1,11) = 5.041$, $p = .046$, $\eta^2_{\text{partial}} = .314$, were significant. The interaction between traffic light phase and fog indicated that when the traffic light was solid green, no difference in maximum deceleration between foggy and non-foggy approaches occurred. When the traffic light changed from red to green, maximum deceleration was stronger when there was no fog in the track compared to when there was fog in the track (Figure 4, right), $F(1,11) = 7.008$, $p = .023$, $\eta^2_{\text{partial}} = .389$.

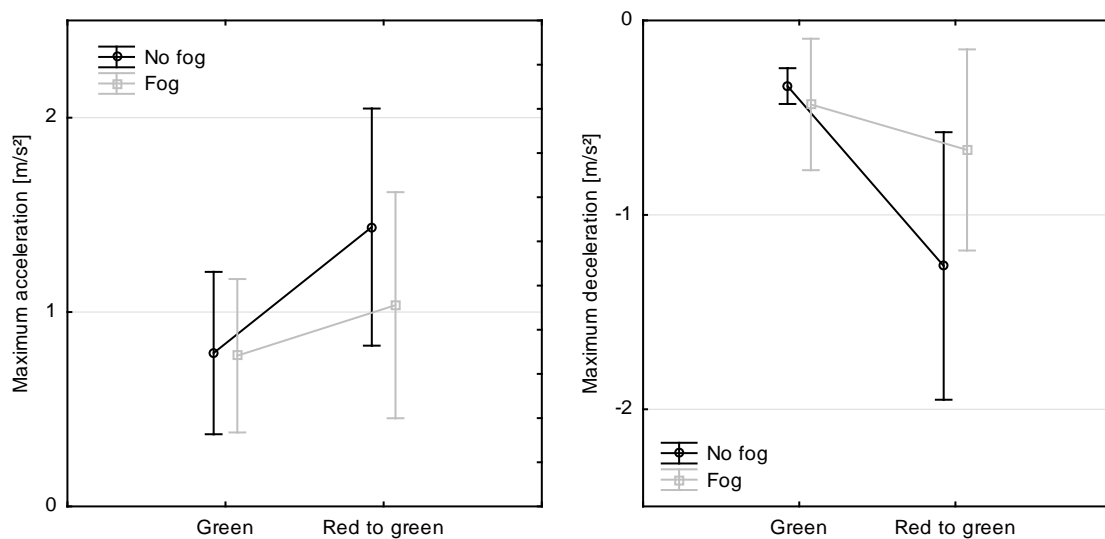


Fig. 4 Means and 95% confidence intervals for maximum acceleration (left) and maximum deceleration (right) in dependence of the factors traffic light phase and fog for approaches without a stop

For the traffic light approaches in which drivers had to stop at the stop line (i.e., red and green to red phase), we investigated maximum acceleration and deceleration with two ANOVAs with the factors traffic light phase, lead vehicle and fog. When drivers had to stop at the intersection, the maximum acceleration occurred after waiting at the red light. The main effect lead vehicle was significant indicating that drivers' maximum acceleration was larger when they started after stopping behind a lead vehicle, $F(1,11) = 7.061$, $p = .022$, $\eta^2_{\text{partial}} = .390$. A possible reason for that is the high acceleration of the lead vehicle which was programmed in order for the lead vehicle to leave the scene before the next traffic light approach started. Drivers might have adapted their driving behaviour to this high acceleration.

More importantly, maximum deceleration was larger when the traffic light changed from green to red compared to a solid red traffic light, $F(1,11) = 8.972$, $p = .012$, $\eta^2_{\text{partial}} = .449$. Additionally, drivers maximum deceleration was larger when there was a lead vehicle compared to no lead vehicle, $F(1,11) = 12.486$, $p = .005$,

$\eta^2_{\text{partial}} = .532$, and when there was fog in the track compared to no fog, $F(1,11) = 11.743$, $p = .006$, $\eta^2_{\text{partial}} = .516$ (Figure 5). No other effects were significant (all $ps > .05$).

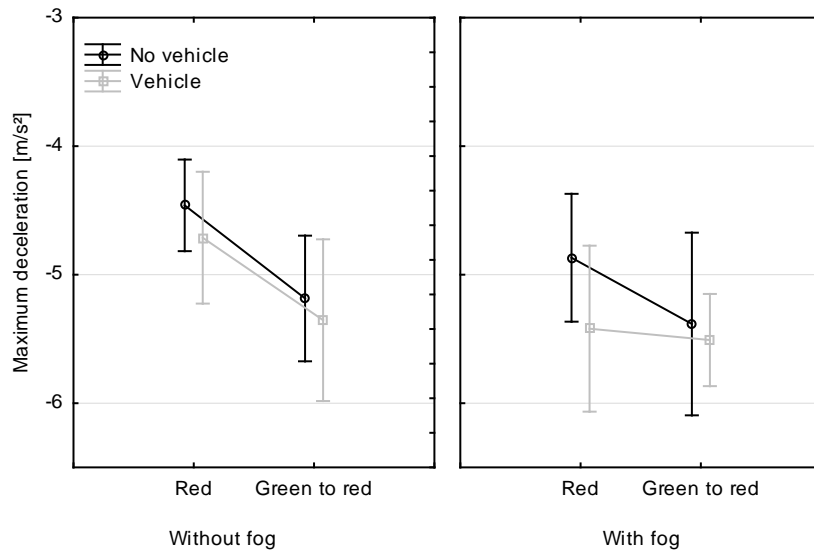


Fig. 5 Means and 95%-confidence intervals for maximum deceleration in dependence of the factors traffic light phase, lead vehicle and fog for approaches with a stop

In summary, maximum accelerations and decelerations were stronger, when the traffic lights changed compared to remaining solid, which was especially true when there was no fog in the track.

To evaluate direct driver input, we listed the percentage of approaches in which participants released the accelerator pedal completely and in which they used the brake pedal.

Table 3 shows that the frequencies for the release of the accelerator pedal and subsequent usage of the brake pedal was low in the solid green condition: In approximately 50% of the approaches, drivers released the accelerator pedal. Hardly any driver used the brake pedal in this condition. In contrast, when the traffic light changed from red to green and there was no fog in the track, drivers released the accelerator pedal in almost all approaches, and drivers started braking in around 50% of the approaches. The frequencies for coasting and braking decreased in the red to green condition when there was fog in the track compared to no fog.

Naturally, in order to stop at the red traffic lights, all drivers released the accelerator pedal and pressed the brake pedal at some point in the approach, which led to 100% accelerator releases and brake onsets for solid red and green to red conditions.

Table 3 Frequencies [%] of traffic light approaches in which drivers released the accelerator pedal and pressed the brake pedal, differentiated for the traffic light phase, fog and lead vehicle conditions

Traffic Light	Vehicle	Fog	Accelerator release	Brake onset
Green	No Vehicle	No Fog	38.89	2.78
	No Vehicle	Fog	54.17	4.17
	Vehicle	No Fog	41.67	2.78

	Vehicle	Fog	62.50	4.17
Red to green	No Vehicle	No Fog	94.44	47.22
	No Vehicle	Fog	66.67	16.67
	Vehicle	No Fog	94.44	50.00
	Vehicle	Fog	66.67	4.17

4 Discussion

We investigated driving behaviour at traffic light intersections with all four possible traffic light states and under different traffic and visibility conditions. There was either a lead vehicle ahead or no lead vehicle and visibility was varied by adding fog or no fog. The four traffic light states of solid green, solid red or changing red to green or green to red were introduced. In the data analysis we showed, that considering different distances to the traffic light, as well as different parameters of driver behaviour like accelerator and brake pedal usage offers valuable information for the investigation of decision making when approaching traffic light intersections. In the discussion, we interpret the observations on driving behaviour, give implications for the development of a driver assistance system, discuss limitations and provide challenges for future research.

4.1 Driving behaviour at traffic light intersections

Participants drove slightly faster than 50 km/h in the free driving situation. Unlike reported in previous research (Van der Hulst, Rothengatter, & Meijman, 1998), drivers did not reduce speed when driving in fog, which is expected to be due to the safe driving simulator setting. When driving behind a lead vehicle, the average speed was slightly lower compared to free driving. Naturally, drivers had to follow the speed limit strictly, when a vehicle was in front. Interestingly, even though drivers already saw the traffic light at a distance more than 180 m in good visibility, they postponed their reaction to it and started releasing the accelerator pedal approximately 50 m after perceiving the traffic light for the first time. This supports results reported by Goh and Wong (2004), who observed that even though drivers saw a traffic light change to red, they felt no need for a reaction towards it, when the distance at which the light changed was large enough. Overall, the crucial area for the traffic light intersection approach ranged between 130 and 50 m in front of the intersection. In areas more than 130 m away from the traffic light, drivers did not yet react to the lights. In distance sections smaller than 40 m in front of the intersection, driving profiles assimilate between the compared conditions. However, it must be noted that the distances measured in the driving simulator might differ from real world data and should therefore be interpreted relative rather than absolute.

When the traffic lights were solid green, drivers passed through the intersections with only slight adaptations of speed and maximum acceleration and deceleration did not differ between the lead vehicle and fog conditions. Nevertheless, drivers showed reactions to the traffic light in 50% of the approaches by releasing the accelerator pedal. This behaviour could be interpreted in terms of an uncertainty that drivers experience when they do not know if a traffic light change will occur (Wickens & Hollands, 2000). In contrast, when the traffic lights changed from red to green, drivers reduced speed as initial reaction to the red traffic light before the traffic light change occurred. This is because the traffic light change occurred later than the participants' threshold for initiating a safe and comfortable deceleration to stop at red. The results support previous research findings. For example, the very first moment of deceleration could not be identified, when starting measuring approximately 105 m in front of the traffic light, because deceleration had already started (Wortman & Matthias, 1983). The reduction of speed in the red to green condition was less strong with low visibility compared to high visibility. Hence, adaptations of driving speed were maximal, when a traffic light phase change occurred and drivers saw the initial red light. In this condition, maximum acceleration and deceleration were larger when there was no fog compared to fog, which can be explained by the more frequent usage of the brake pedal. Moreover, the influence of fog was increased when there was no vehicle ahead. The lead vehicle seemed to act as an orientation in adverse conditions. The potential for improvements in driving efficiency when crossing the intersection without a stop are therefore largest when the drivers are in a free driving state, when the traffic light changed from red to green and when there was no fog in the track. In the solid green conditions the potential for improvements of efficiency are low. In this condition, the focus of a driver assistance system might be to reduce insecurity about the timing of the traffic light state.

When the traffic light was solid red and the visibility was good, drivers adapted their driving speed earlier than in the changing green to red condition. In the green to red condition, driving profiles for the lead vehicle and fog conditions did not differ when considering the start of speed reduction. The traffic light phase change and the reduced visibility by fog seemed to have similar effects on driving behaviour: both variations postponed the reduction of speed, because they only allowed drivers to initiate the driving behaviour required for the current traffic light phase later than drivers naturally initiate the required driving behaviour (in the solid red condition with good visibility). Therefore, maximum decelerations were stronger when the traffic light changed from green to red compared to the solid red condition. The maximum deceleration values in our setting were higher than the maximum decelerations reported in previous research (e.g., Wang, Dixon, Li, & Ogle, 2005). This might be due to the driving simulator setting, in which the missing dynamic feedback can lead to higher absolute deceleration values than observed in real traffic conditions. In general, in the present setting, drivers had time to decelerate

comfortably to standstill and did not experience urgent braking scenarios. As expected by results of previous research (El-Shawarby, Rakha, Inman, & Davis, 2006), we observed a 100% probability of stopping at the red traffic light with an amber onset at 80 m in front of the traffic light. Again, the presence of a lead vehicle reduced the influence of the fog on driving behaviour.

In summary, drivers showed the most efficient initiation of a stop at red when the traffic light did not change, when there was a lead vehicle ahead and when visibility conditions were good. Thus, the potential for improvements in efficiency are highest when drivers see a traffic light phase change (in the green to red condition, without fog) and when there is no lead vehicle ahead, when assuming that lower decelerations to initiate the stop at red are more efficient. In these situations, the extended information from a traffic light assistant could support drivers with increasing driving efficiency by reducing deceleration strength.

We suggest that approaching traffic light intersections should be subdivided in three phases (Figure 6). During the orientation phase, drivers see the traffic light intersection, but do not adapt their driving behaviour towards it. This seems reasonable, because at this stage the traffic light phase and with that the required driving behaviour might still change. In our study, fog obscured the view of the traffic light intersection, hence drivers were in a free driving state for a longer period of time. Following this initial phase, drivers started reacting to the upcoming traffic light in a preparation phase starting around 150 meters in front of the intersection in our study. The preparation phase is characterised by drivers reducing speed by releasing the accelerator pedal in order to prepare for cues in the environment that trigger their decision on how to proceed. The end of the preparation phase is defined by either a traffic light change that gives a clear indication on the phase at which drivers will arrive (in our study around 80 meters in front of the intersection) or by the drivers' decision to proceed or stop no matter of any further traffic light phase change. Then the realisation phase starts, in which drivers initiate the required behaviour, i.e. either proceeding through the green light or stopping at a red light. In our study, drivers did not experience any safety critical traffic light changes. However, even though the traffic light changes occurred early enough to prevent urgent braking, dynamic driving behaviour differed between the variations of lead vehicle and visibility. This is due to the observation that the realisation phase started earlier than the traffic light change occurred and drivers started preparing to the traffic light earlier in the non-fog conditions than in the fog conditions.

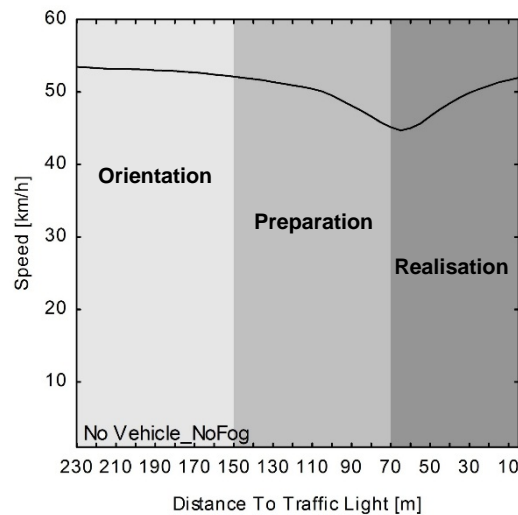


Fig. 6 Speed profile for approaching a red to green traffic light phase without lead vehicle and without fog. Highlighted are the three approach areas orientation, preparation and realisation

Overall, we assume that the results of our study underestimate the influence that our factors could have on driving behaviour and with that the influences of traffic and visibility conditions on efficiency. Due to the controlled driving simulator setting and the restriction that traffic light changes always occurred 80 m in front of the intersection, the traffic situations were easier to predict than in real traffic. It can be argued that in real traffic with more variable traffic conditions, effects of our variations might exceed the effects shown in the present results.

4.2 Implications for driver assistance systems

The results have implications for the development of a driver assistance system and show a potential for increasing driving efficiency when approaching traffic light intersections. The driver assistance system is based on information coming from different sensor systems, mainly car to infrastructure communication. The gathered information about the traffic environment and traffic light phase durations will enable to instruct driving recommendations to the driver when approaching traffic light intersections in any of the four possible traffic light states. As a result, there will be either recommendations on the speed to choose when planning to cross the intersection at green, or recommendations on how to stop efficiently in an unavoidable red phase. Past research with traffic simulation tools has shown that the optimum fuel saving of a traffic light assistance system occurs when the information is given between 100 and 500 m in front of the traffic light (Tielert, et al., 2010). The car to infrastructure communication will enable information to be available approximately 300 to 600 m in front of the intersection in urban settings (U. Eberle, personal communication, November 11, 2014). From our results, when drivers approached green or red to green traffic lights, deceleration could be avoided when additional information on the traffic light phasing was presented earlier than around 150 meters in front of the intersection. Being aware

of a red traffic light led to more efficient traffic light approaches when drivers saw the solid red light at least 100 meters in front of the intersection compared to a later visibility of the solid red light.

The findings of this study provide different conclusions regarding driving behaviour at traffic light intersections. First, the information the traffic light assistant will give to the driver will be available earlier than the drivers usually see the traffic light in urban settings and earlier than they start their reaction towards the traffic light naturally. Hence, the system will interfere in normal driving behaviour and decision making. The extent to which the system interferes in normal driving behaviour then depends on various system parameters and situational circumstances, like for example the distance between consecutive traffic lights, surrounding traffic, speed limits, car engine characteristics or programme timings, which should be the scope of future research. Additionally, we saw that driving behaviour differed according to the foresight drivers had of the traffic light intersection. With fog, drivers showed different speed and acceleration profiles compared to without fog. In the present setting without any system interference, driving behaviour changed towards higher efficiency when drivers merely saw the traffic light earlier. Informing the driver earlier about the presence of an upcoming traffic light has a potential to change driving behaviour towards more efficiency.

However, the findings also show that one characteristic of the orientation phase is that drivers do not adapt their behaviour towards the traffic light, even though they already know about its existence, and can already see the current state. This is because they do not yet see a necessity to adjust their behaviour. Thus, the driver assistance system could help emphasising the advantages of reducing speed by initiating coasting or sailing episodes earlier than the drivers naturally do under good visibility conditions.

In addition, by informing the driver about the current and future traffic light states, the anticipation of the development of the traffic rules at the intersection is improved. As shown in the present study, during the preparation phase, drivers started to initiate behaviour to traffic light states, which subsequently changed during the approach. We described that the higher visibility in the conditions without fog was only beneficial in terms of more appropriate driving behaviour, when no traffic light change occurred during the approach. A driver assistance system that receives information regarding the duration and sequence of traffic light phases could help drivers to avoid preparing for a phase that might change soon. For example, with the information from the traffic light assistant drivers could abstain from braking when the traffic light changes from red to green.

In the realisation phase, the assistance system will especially focus on the specific instruction of efficient driving behaviour. For example, we saw that after deciding to proceed through the green light in a red to green condition, drivers accelerated instead of keeping speed constant. A system trying to support efficiency should instruct less strong accelerations and trigger more continuous driving. Another example for a potential support of

the assistance system can be seen in the 100% brake pedal usage when stopping at the traffic light; with the traffic light assistant drivers could be instructed to decrease speed by coasting.

In sum, the traffic light assistance system should communicate different information units to the driver. Information on the traffic light phasing could include the phase duration of the current traffic light phase, timing for a transition to the next traffic light phase or a highlight for the traffic light phase at which drivers will arrive at the intersection. Recommendations for the required driving behaviour could include appropriate driving speeds or appropriate driving behaviours.

4.3 Limitations and future steps

The study was conducted in an urban setting with low complexity. We wanted to avoid creating cues about the right of way rules at the intersections and therefore excluded other traffic than the experimental variation of the lead vehicle. Further studies should include more complex road scenarios and traffic conditions. This would help to increase the understanding of the cues drivers use from the intersection situation in order to make their decision on how to proceed.

Additionally, by the high standardisation of the intersection situations (same layout, same traffic light phase durations and phase changes) and the high number of repetitions, we might have reduced the external validity, because the uncertainty about the development of the traffic situation decreased. This is confirmed by the missing reduction of average driving speed in the fog conditions compared to the non-fog conditions that has previously been observed in real traffic conditions. However, as mentioned above, the low complexity might lead to an underestimation rather than an overestimation of effects. With increasing insecurity on traffic light phasing and changing times, the benefits of the driver assistance system might increase. Nevertheless, future research should indicate if the results transfer to real traffic situations and to larger and fully gender balanced sample sizes. Along with that the distances to the traffic light reported in the present study can only be interpreted relatively and a transfer to real-world scenarios remains to be proven in future research.

The future focus in the investigation of the driver assistance system will be the evaluation of the information strategy along with positive effects and potential negative effects of the traffic light assistant. Based on the current discussion, we attempt to influence driving behaviour by presenting information on traffic light phasing and required driving behaviour. Furthermore, with the background that the driver assistance system changes normal driving behaviour, we will examine the influence of driving with the system on interactions between equipped and non-equipped road users.

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