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The impact of the connected environment on driving behavior and safety: A driving simulator study

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Abstract

The connected environment provides surrounding traffic information to drivers via different driving aids that are expected to improve driving behavior and assist in avoiding safety-critical events. These driving aids include speed advisory, car-following and lane-changing assistances, and advanced information about possible unseen hazards, among many others. While various studies have attempted to examine the effectiveness of different driving aids discretely, it is still vague how drivers perform when they are exposed to a connected environment with vehicle-to-vehicle and vehicle-to-infrastructure capabilities. As such, the objective of this study is to examine the effects of the connected environment on driving behavior and safety. To achieve this aim, an innovative driving simulator experiment was designed to mimic the connected environment using the CARRS-Q Advanced Driving Simulator. Two types of driving aids were disseminated in the connected environment: continuous and event-based information. Seventy-eight participants with a diverse background drove the simulator in four driving conditions: baseline (without driving aids), perfect communication (uninterrupted supply of driving aids), communication delay (driving aids are delayed), and communication loss (intermittent loss of driving aids). A variety of key driving behavior indicators were analyzed and compared across various routine driving tasks such as car-following, lane-changing, interactions with traffic lights, and giving way to pedestrians at pedestrian crossings. Results suggest that drivers in the perfect communication maintain a longer time-to-collision during car-following, a longer time-to-collision to pedestrian, a lower deceleration to avoid a crash during lane-changing and a lower propensity of yellow light running. Overall, drivers in the connected environment are found to make informed (thus better) decisions towards safe driving.

Keywords: Connected environment; Advanced driving simulator; Car-following; Lane-changing; Driving Behavior; Safety

1. Introduction

Communication and sensing technologies are believed to revolutionize road transport and alter how humans travel and interact with road traffic infrastructure. More specifically, it is anticipated that these technologies can help in solving massive transport issues related to mobility, efficiency, safety, and environmental impact. An application of such technologies is the connected environment where information is disseminated via vehicle-to-vehicle, vehicle-

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to-infrastructure, and vehicle-to-everything communications. The information, in the form of driving aids, is expected to assist in routine driving tasks, such as car-following, lane-changing, interaction with pedestrians and traffic lights, where drivers require information about surrounding traffic.

In 2010, the National Highway Traffic Safety Administration (NHTSA) reported that vehicle crashes killed about 33,000 people, caused 3.9 million injuries, and damaged 24 million vehicles, and the estimated economic cost of these crashes was about $242 billion (Blincoe et al., 2015). NHTSA suggested that 94% of these crashes were associated with human errors (NHTSA, 2017). More specifically, 17.8% crashes occurred due to exceeding the posted speed limit, rear-end collisions and sideswipes respectively contributed to 6.8% and 2.6% of the total crashes, 15.5% crashes involved colliding with pedestrians, and 4% of crashes involved drivers disobeying the traffic rules such as traffic signals. Connected and automated vehicles in the near future are expected to reduce road traffic crashes magnificently.

Drivers can make various errors during routine driving tasks that lead to crashes, as reported above. In traditional driving, surrounding traffic information is processed by drivers based on their limited perception, attention, memory, and judgment capabilities (Sharma et al., 2017). The information exceeding drivers' capabilities tends to increase the drivers' workload resulting in inaccurate decisions, leading to safety-critical events (Salmon et al., 2005).

Routine driving tasks include car-following, lane-changing, merging to and exiting from the motorway, interacting with pedestrians, obeying traffic signs and lights in urban situations, etc. These driving tasks are engaging in nature and can be stressful, and drivers are required to continuously monitor surrounding traffic conditions and the route progress in order to make efficient and safe driving decisions. In a car-following situation, for instance, a driver needs to maintain an appropriate gap to the leader (i.e., spacing) in order to safely control their maneuver in case the leader suddenly brakes.

To this end, the connected environment provides various driving aids through messages and/or warning that can help drivers in making better driving decisions. Notably, the speed of and the distance to the leader in the current lane can assist in the car-following situation (Wang et al., 2016); the information of subsequent gaps available in the adjacent lane can reduce the uncertainty associated with gap acceptance during lane-changing (Nie et al., 2016); advanced information about unseen events, like congestion and lane closure, can provide enough time to drivers for better decision-making; advisory information about interactions with pedestrians and traffic lights can minimize crash risk (Hashimoto et al., 2016); and warning information about exceeding the posted speed limit or when driving too close the leader can potentially reduce the probability of engaging in safety-critical events. On the other hand, these messages and warnings can also increase the mental workload of drivers who have to deal with a greater number of data and information from the connected environment, and thereby can deteriorate driving performance (Strayer et al., 2019). However, there is no concrete evidence of such negative impacts of the connected environment on driving behavior. Now the question arises: can drivers improve their decisions and react to the information from the connected environment effectively? Or will drivers be misled by the connected environment and thereby make wrong driving decisions and mistakes? These are some of the (many) questions that motivate the present study.

The synthesis of literature on the connected environment suggests that most of the studies are mainly performed in a numerical simulation environment (Lee and Park, 2012, Park et al., 2011, Talebpour et al., 2016, Chakroun and Cherkaoui, 2016, Njobelo et al., 2018), which lacks human factors that are critical in evaluating safety and success of the connected environment. Besides, driving tasks are different from each other, such as car-following versus lane-changing, and thus require different information for making efficient decisions. Analyzing the impact of various driving messages on the corresponding driving tasks using the real data from the connected environment can assist in quantifying the impact of the connected environment across various driving maneuvers and traffic interactions, and identifying the groups of drivers that are influenced by the connected environment.

As such, the objective of this study is to examine the effects of the connected environment on driving behavior and safety. To achieve this objective, an innovative driving simulator experiment was designed incorporating various routine driving tasks into the connected environment. Drivers' responses to different driving aids provided by the connected environment, such as continuous information, advanced advisory information, warning information, and lane-changing assistance, are analyzed on motorways and city streets.

This paper is organized as follows: Section 2 reviews representative studies from the literature. Section 3 explains the design of the experiment, including scenario development, vehicular interactions, information design, and data processing. Section 4 presents results, and Section 5 discusses the impact of various driving aids on different driving behavior. Finally, Section 6 summarizes the main conclusions and suggests future research directions.

2. Literature review

Since this study analyzes the impact of the connected environment on various driving tasks, this section is divided into four subsections based on driving tasks, namely car-following behavior in the connected environment, lane-changing behavior in the connected environment, the impact of the connected environment in urban context, and macroscopic benefits of the connected environment.

2.1 Car-following behavior in the connected environment

Connected vehicles are designed to provide assistance to drivers to efficiently perform various routine driving tasks. For car-following scenarios, Chen et al. (2005) quantified the safety benefits of in-vehicle information systems and reported the right-skewed frequency of drivers' perception-reaction time. More specifically, the crash rates with and without the system were respectively 0.12 and 0.06. Ho et al. (2006) reported the benefits of vibrotactile warning signals to avoid rear-end collisions during the car-following situation and concluded that drivers responded more quickly to the situation, and a higher safety margin was obtained with the warning signal compared to when it was not presented. Baldwin (2007) analyzed the impact of the auditory warning message on crash avoidance in high crash risk scenarios during car-following tasks. This study found that the crash rate was significantly reduced when the system was active, and its impact was more prominent for older drivers (i.e., over 65 years). Similarly, another study examined the effectiveness of tactile warning messages during a car-following scenario, which revealed that the driver with a tactile warning had the shortest mean reaction time compared to driving without a tactile warning (Scott and Gray, 2008). Birrell and Young (2011) analyzed the impact of smart driving messages provided by in-vehicle information systems in a car-following task and found that the system decreases the mean driving speed in simple and complex driving scenarios. In a follow-up study, Birrell et al. (2012) reported that the information provided by the in-vehicle system helped drivers avoiding hard decelerations and maintaining a safe headway, proper lane positions, and small lane deviations.

2.2 Lane-changing behavior in the connected environment

Lane-changing, a lateral and one of the complex driving tasks that require traffic information, is performed when a driver is required to leave the current lane to reach the lane guided by designed roadway (i.e., mandatory lane-changing) and to achieve better driving conditions (i.e., discretionary lane-changing). A smart advisory information system for lane-changing response time and distance has been reported to instruct drivers efficiently, resulting in lower lane-changing durations (Li et al., 2015). Mai et al. (2016) evaluated the effectiveness of lane-changing distribution advisory in a weaving section implemented in a micro-simulator and reported that the proposed advisory could significantly improve traffic delay. Chakroun and Cherkaoui (2016) simulated lane-changing advisory information generated from vehicle-to-vehicle communication at different market penetration rates and found that even a lower penetration rate of 10% can reduce total travel time. Similar findings were also reported in Jin et al. (2014).

2.3 The impact of the connected environment in an urban context

The aforementioned studies mainly describe car-following and lane-changing on a motorway. On the other hand, driving in the urban environment with interactions with traffic lights and various road users like pedestrians and cyclists is often task demanding. Driving assistance systems ought to improve driving performance in such scenarios. Chang et al. (2009), for instance, evaluated the performance of an intersection collision warning for a signalized intersection and found that drivers driving with the system had a shorter reaction time, drove with a lower speed, and had a lower crash risk compared to driving without the system. Similarly, Xiang et al. (2016) evaluated the effectiveness of auditory warning message on brake response time to a red-light running and found that an auditory warning message significantly reduced braking time and collision occurrence rate. Njobelo et al. (2018) proposed an advanced stop assist system for signalized intersections by utilizing vehicle-to-infrastructure communication, which is implemented in a microsimulation. The simulations showed that with a 100% market penetration rate, the system reduced the hard braking by about 50%. Furthermore, Sam et al. (2015) proposed a driver alert system using the hybrid vehicular ad-hoc network to avoid vehicle-pedestrian crashes, and the simulation results revealed that the chances of crashes with a pedestrian reduced drastically, when the system was activated.

2.4 Macroscopic (or network-wide) benefits of the connected environment

Since the connected environment is not in operations at a large scale, past studies have mainly reported various benefits of the connected environment using numerical simulations. Olia et al. (2016), for example, developed a modeling framework based on microsimulation for the connected vehicles (vehicles operating in the connected environment) and reported that these vehicles improved traffic mobility, enhanced safety, and reduced greenhouse gas emissions at a network level. Various other studies reported similar benefits of connected vehicles (McGurrin et al., 2012, Zeng et al., 2012). Rahman and Abdel-Aty (2018) proposed a high-level control algorithm for connected vehicles on expressways and found that the connected vehicle platooning increased safety measured in terms of safety surrogates. Similarly, a connected vehicle intersection control algorithm was proposed by Lee and Park (2012) that did not require a traffic signal at intersections. Using microsimulations, this study demonstrated that compared to the conventional actuated intersection control, the connected vehicle intersection control algorithm reduced stop delay and travel time by 99% and 33%, respectively. In addition, basic safety messages obtained from the safety pilot model deployment project were reported to improve driving decisions and assist in intersection safety evaluation (Lee and Park, 2012). Park et al. (2011) provided a merging advisory in a microsimulation framework and found a 6.4% increase in average speed with a 5.2% reduction in emissions. Similarly, using the merge assistance provided by the connected environment, Ahmed et al. (2017) showed that drivers with the system can collaborate and safely merge to a freeway. Talebpour et al. (2016) analyzed speed harmonization under the connected environment and concluded that shock waves can be properly detected and prevented from propagating to upstream by providing speed advisory to the traffic. Although the macroscopic benefits of connected vehicles or environments are reported in the literature using numerical simulations, our understanding of the impact of the connected environment, more specifically different driving aids, on microscopic driving behavior and safety remains elusive.

3. Experimental Design and data collection

Due to the novelty of the connected environment and the scarcity of relevant data, an innovative driving simulator experiment was designed to collect high-quality vehicle trajectory data for the connected environment using the Centre for Accident Research and Road Safety-Queensland (CARRS-Q) Advanced Driving Simulator. Figure 1 presents a flow chart summarizing all the scenarios and traffic interactions considered and analyzed in this study. There were four driving conditions, namely, baseline, perfect communication, communication delay, and communication loss. The driving simulator experiment included traffic interactions on motorways and in city road traffic environments. Traffic interactions on the motorway included high-speed and low-speed car-following tasks, and mandatory and discretionary lane changing tasks. On the other hand, traffic interactions in the city environment included interactions with the traffic light change at signalized interactions and interactions with pedestrians at pedestrian crossings. The durations of traffic interactions in the city were short in nature (more information on this later), and thus, it was not possible to simulate communication delay and communication loss scenarios in the simulator. Therefore, these interactions were studied in the baseline and perfect communication driving conditions only. A detailed description of each scenario and all the traffic interactions are provided in the ensuing subsections.

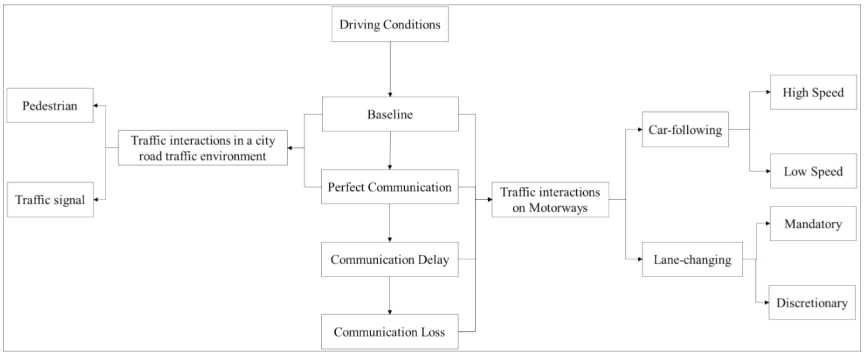


Figure 1. Driving conditions and traffic interactions designed for the driving simulator experiment

3.1 Advanced Driving Simulator

The simulator consists of a fully functioning Holden Commodore car and the three front-view projectors, providing a 180º field of view. To mimic the real-life driving and vehicle interaction with road features, the simulator car was fixed with a six-degree-of-freedom rotating base that could move and rotate in all three directions. The simulator software (i.e., SCANeR™ studio) was connected to eight computers that linked vehicle dynamics with a virtual road environment. The simulated road environment and traffic interactions were displayed at a rate of 60 Hz whilst the advisory and trajectory data were collected from the advanced driving simulator at a rate of 20 Hz.

3.2 Participants

Seventy-eight participants (35.9% females), with diverse backgrounds, were recruited by advertising at various public places and social media platforms. The participants aged between 18 to 65 years, and the mean ages for male and female participants were respectively 34.1 (SD 12.6) and 24.9 (SD 6.7) years. Among 78 participants, 38, 32, and 8 participants were respectively young (18–26 years), middle-aged (27–50 years), and older (> 50 years) drivers. It was a prerequisite that a participant must hold a valid Australian driving license. The average driving experience of the participants was 12.2 (SD 11.5) years.

3.3 Experiment design

The driving simulator experiment consisted of driving along motorways and in the city road traffic environment. The entire road geometry is presented in Figure 2, where different road sections, and various traffic events and vehicular interactions are numbered. The motorway section was divided into two parts: two-lane two-way highway and four-lane two-way motorway, which was connected to the Brisbane Central Business District (CBD) by an off-ramp. The city was then further connected to two-lane two-way highway via an on-ramp, and the scenario ended soon after merging to the highway (Figure 2). The geometric features, lane markings, and road signs in the simulator were designed in accordance with the Australian standards. The city streets and the surrounding environment included a detailed simulation of Brisbane CBD with a great deal of accuracy. Each road section had different vehicular interactions that are explained below.

3.3.1 Car-following scenario

A two-lane two-way (single lane in each direction) highway of 3 km long (Section 1 in Figure 2) was designed for the car-following scenario where the participants followed a platoon of vehicles. The leading cars (LVs hereafter) followed the pre-specified speed profile, as shown in Figure 3, whereas the participants' car-following behavior was at their discretion. It can be observed in Figure 3 that two speed profiles were designed, namely high-speed car-following and low-speed car-following.

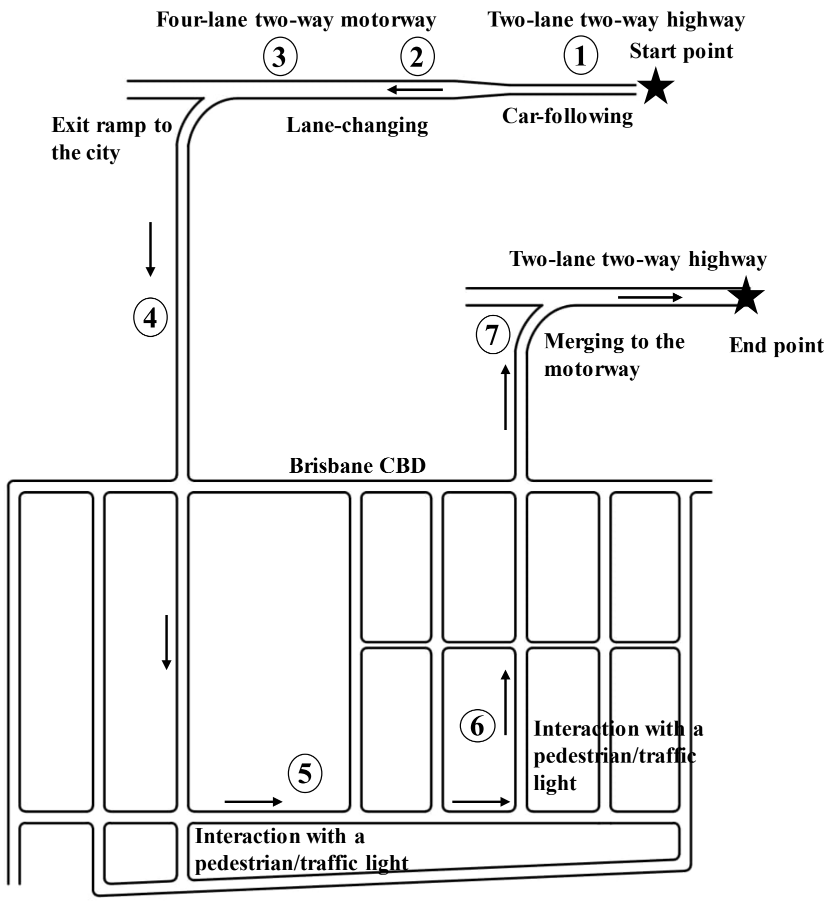


Figure 2. Schematic diagram of the experiment route (not in scale)[2]

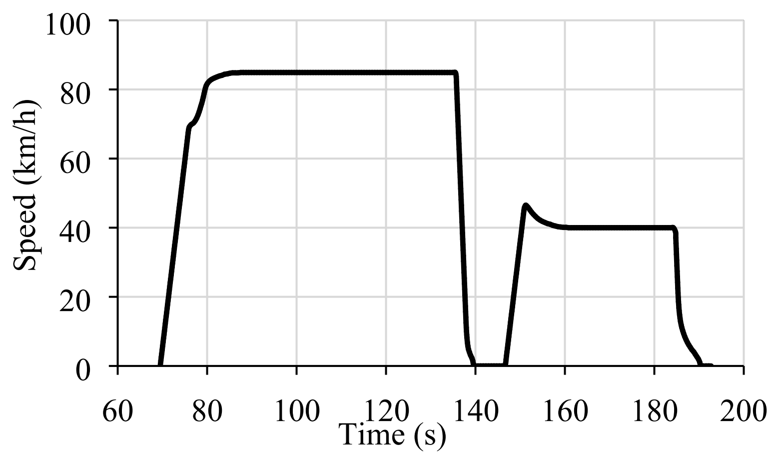
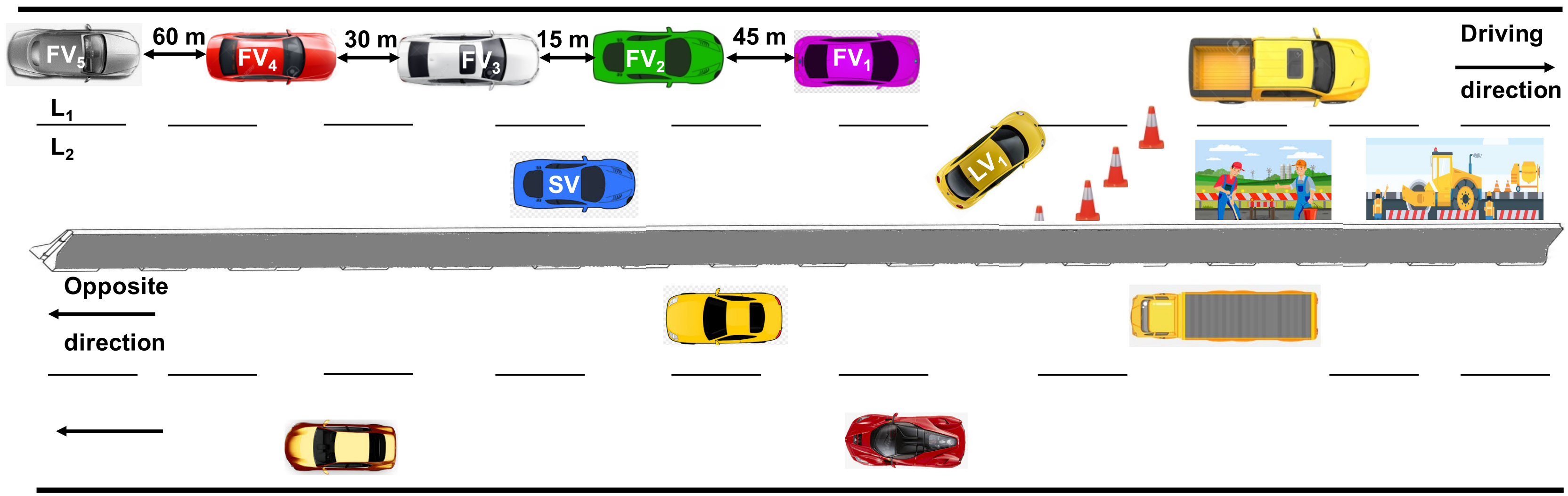
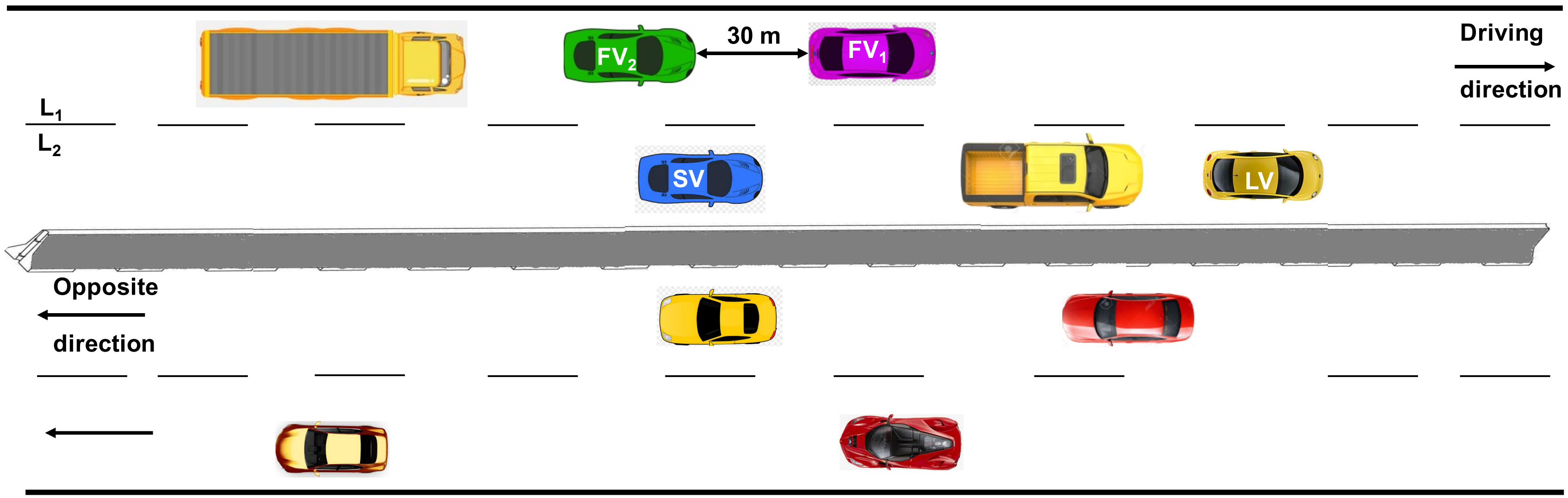


Figure 3. A typical speed profile of the leading car in the car-following scenario (along Section 1 of Figure 2).

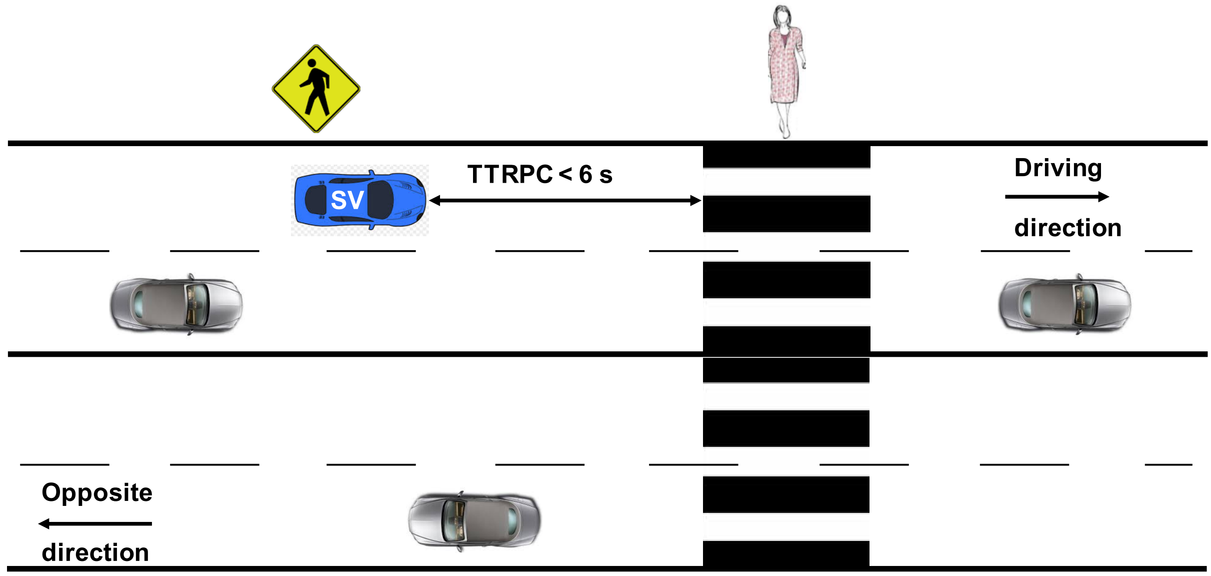
[2] The design of vehicular interactions on each road section are provided in Figure 4.


60 m
30 m
15 m
45 m
FV_5
FV_4
FV_3
FV_2
FV_1
Driving direction
L_1
L_2
SV
LV_1
Opposite direction

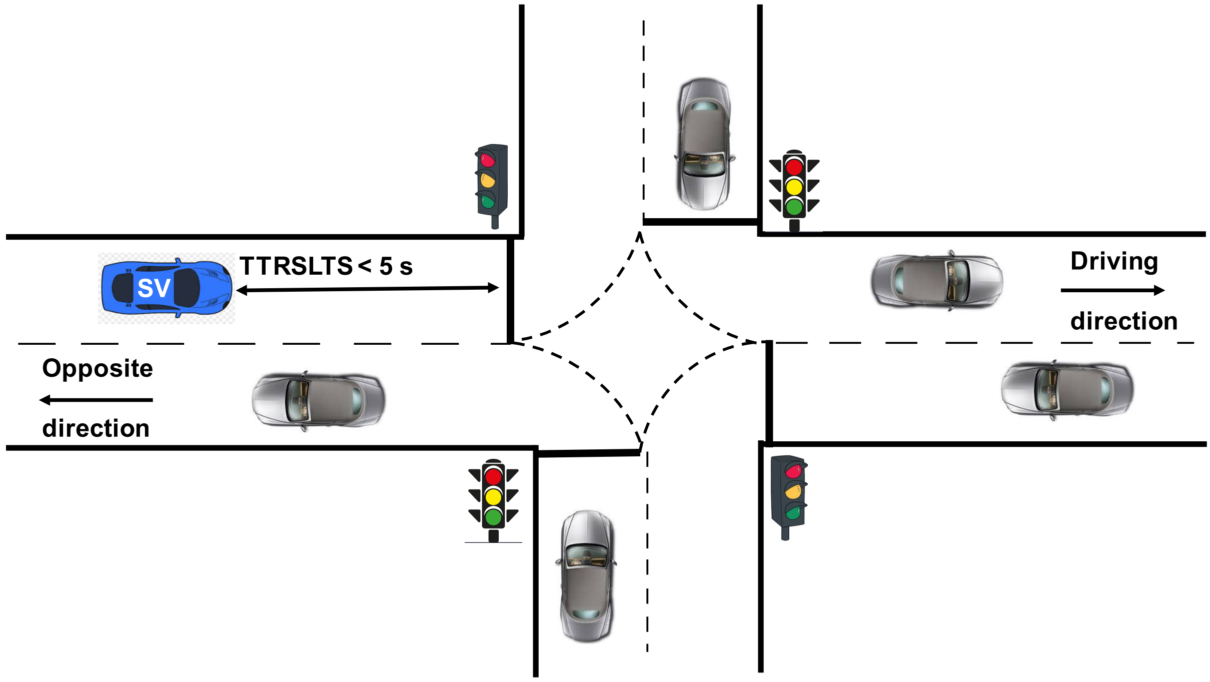
(a)


FV_2
30 m
FV_1
Driving direction
L_1
L_2
SV
LV
Opposite direction

(b)



(c)



(d)

Figure 4. Vehicular interactions during: (a) mandatory lane-changing; (Section 2 of Figure 2) (b) discretionary lane-changing (Section 3 of Figure 2); (c) Time-to-reach pedestrian crossing (TTRPC) (Section 4 of Figure 2); and (d) Time to reach stop line at the traffic light (TTRSLTS) (Section 5 of Figure 2)

In the car-following section, four driving regimes for trajectory completeness, as illustrated by Sharma et al. (2018), were designed, namely acceleration, following, deceleration, and standstill. LV accelerated at a rate of 1.5 m/s^2 until it attained the speed of 85 km/h during the high-speed car-following. Then, LV maintained a constant speed of 85 km/h for around 50 s followed by a hard deceleration at a rate of -4.5 m/s^2. LV then came to a standstill position and maintained such a state for the next 5 s. In the low-speed car-following, LV repeated the same cycle of acceleration, following, and deceleration but with the maximum speed of 40 km/h. The car-following scenario ended after this cycle, and two-lane two-way highway was connected to a four-lane two-way (two lanes in each direction) motorway, where programmed vehicles were waiting for the subject vehicle for other programmed vehicular interactions.

3.3.2 Lane-changing scenario

Both mandatory and discretionary lane-changing scenarios were considered in this study. A four-lane two-way median separated motorway of about 3.2 km long was allocated for the two lane-changing scenarios. In the first section (Section 2 in Figure 2), the current lane (L_2) was closed due to a work zone at about 700 m away from the start of the scenario, and the subject vehicle (SV hereafter) was required to perform a mandatory lane-changing (Figure 4a). The following vehicles (FVs hereafter) in the target lane (L_1) created five mandatory lane-changing gaps ranging from 15 m to 90 m. SV can select any gap from available gaps and enter into the work zone. After traveling about 200 m, the work zone ended, and the immediate LV moved to L_2 and traveled with high speed. The SV had an option to either move to L_2 and drive at high speed or stay in L_1 and follow a slow truck. The discretionary lane-changing scenario started when the SV moved to L_2. In the discretionary lane-changing scenario (Section 3 in Figure 2 and Figure 4b) the LV started moving slowly in front of SV in L_2. Meanwhile, FVs in the target lane (L_1) were moving at a high speed and tempted SV for a discretionary lane-changing. Analogous to the mandatory lane-changing event, five discretionary gaps were provided to SV for lane-changing. Note that SV could select any gap from the five available gaps during the discretionary lane-changing event, and the rest of the following vehicles started to move at a predefined speed. The end of the discretionary lane-changing section was connected to the city via an off-ramp.

3.3.3 Traffic interactions in the urban environment

After exiting from the motorway, the participants entered into the simulated Brisbane CBD area. To realistically represent the surrounding environment of the Brisbane CBD, a detailed simulation of Brisbane CBD with a great deal of accuracy was carried out. The posted speed limit in the city was 40 km/h, and the roads had two lanes in each direction. The city route consisted of two main traffic events, including interactions with a pedestrian entering a zebra crossing from the sidewalk and interactions with a traffic signal change (that is, green light to yellow light) at a signalized intersection.

After exiting from the motorway, drivers entered the CBD (Section 4 in Figure 2), where no traffic event occurred. The motive was to let drivers familiarize themselves with the city driving after driving on the motorway. At the end of Section 4, drivers took a left turn and entered in Section 5 (Figure 2), where the first event occurred. Note that all other possible turning maneuvers at the intersection were blocked by cones to guide the navigation within the city.

The first event in the city was interacting with a pedestrian, where a driver needed to respond to a pedestrian entering a pedestrian crossing from the sidewalk, as shown in Figure 4 (c). The pedestrian crossing was designed by an appropriate zebra crossing marking and a traffic sign in accordance with the Australian standards. Note that there were two zebra crossings along the driven route within the city; however, the pedestrian started to walk on only one of the zebra crossings. The pedestrian-SV interaction event was scripted in a way that the pedestrian started to walk from the sidewalk towards the zebra crossing when the time to reach the pedestrian crossing by SV was less than 6 s.

After interacting with the pedestrian, drivers took a left lane to enter Section 6 (Figure 2), where the second event in the city occurred, i.e., a traffic light turning red from green. In this event, the driver was required to make a decision to stop or run the yellow light (Figure 4 (d)). The traffic light was scripted in a way that the traffic light turned from green to yellow when SV was 5 s away from the stop line. Note that the amber phase (i.e., yellow light) between the red and the green phase was 3 s.

3.3.4 Design of the connected environment

The participants in the connected environment received an uninterrupted supply of information in the form of driving aids, mimicking vehicle-to-vehicle and vehicle-to-infrastructure communications. Following the majority of vehicle manufacturers and their in-vehicle information systems, the designed connected environment in this study provided driving aids through both visual and auditory forms. This design also resembles the heads-up display systems equipped in the recent vehicle models.

In the connected environment, two types of driving messages were disseminated including continuous and event-based information. Continuous information (Figure 5(a)) was continuously presented on the bottom left corner of the windscreen, informing about the driving conditions in the current lane like the speed of and the distance to LV in the current lane. Event-based driving messages included warnings for critical situations, lane-changing messages, and advisory information about upcoming traffic interactions. A warning message with a beep sound appeared during critical situations like exceeding the posted speed limit and getting too close to the LV, i.e., tailgating warning. When a participant exceeded the posted speed limit (Figure 5(a)), a speed limit sign flashed up with a beep sound. Similarly, when a participant drove too close to LV (TTC $\leq$ 1.5 s) on the current lane, the spacing sign flashed up with a beep sound. Meanwhile, when a lane-changing opportunity is available in the adjacent lane, a lane change message (Figure 5(b)) popped on the left corner of the windscreen. The blue and red cars (Figure 5(b)) refer to SV in the current lane and FVs in the target lane, respectively. In addition, the designed connected environment provided event-based advanced advisory aids to drivers for traffic events like traffic light change at signalized intersections (Figure 5(c)) and pedestrians' presence on the zebra crossings (Figure 5(c)). The advanced information about the change in traffic light was provided when SV was 5 s away from the stop line. Similarly, the information on the pedestrian entering the pedestrian crossing was provided when the time to reach the pedestrian crossing was less than 6 s. Several other advisory messages (displayed in the text form along with a beep) were also provided in the connected environment such as information on the evasive action of LV in the current lane (i.e., hard braking), lane-closure due to work zone, and the distance to the exit ramp.

Vehicular interactions during all the driving tasks remained the same in all four driving conditions: baseline, perfect communication, communication delay, and communication loss. The only difference was that the driving aids were provided in the connected environment scenarios but not in the baseline condition. In the communication delay scenario, the event-based driving aids were delayed by 1.5 s. The delay of 1.5 s was selected based on a pilot study in which different delays (i.e., 0.5, 1, 1.5, and 2 s) were tested, and the minimum delay at which participants started to react/notice was selected. The selected delay of 1.5 s is also aligned with Talebpour et al. (2016), which reported a negative impact of delay on traffic safety. Furthermore, in the communication loss scenario, the participants faced an intermittent loss to the connected environment and did not receive any driving aids. The communication delay and communication loss scenarios were only programmed for the motorway environment where car-following and lane-changing interactions were located. A complete list of traffic interactions considered across four driving conditions is shown in Table 1.

Table 1. Traffic interactions considered across various driving conditions in the simulator experiment

Traffic Interactions	Baseline	Perfect communication	Communication delay	Communication loss
High-speed car-following	✓	✓	✕	✓
Low-speed car-following	✓	✓	✕	✕
Mandatory lane-changing	✓	✓	✓	✕
Discretionary lane-changing	✓	✓	✓	✓
Pedestrian crossing	✓	✓	✕	✕
Traffic light	✓	✓	✕	✕

✓: considered; ✕: not considered

The suitability and associated workload of driving aids were carefully tested and examined during the pilot testing. In addition, all the participants performed a practice drive to become familiar with the simulator vehicle, driving environment, and all the driving messages that were transferred during the experimental drive. Note that compliance with the information was left at the discretion of the participants.

A number of strategies were implemented to control for learning effects. First, the driving scenarios were randomized. Second, the driving environment, surrounding vehicles, and their color were also changed across the drives. Third, in each drive, there were multiple events on the motorway and in the city environment, and the participants were required to take a short break after each drive. A participant took about 10-12 minutes to complete each drive, and the total time to complete the experiment was about an hour, and thus, it was very unlikely for a participant to remember a particular event.

A participant testing protocol was developed for this experiment. The participants arrived at the CARRS-Q facility, where they were briefed about the objective of the study. The participants were also informed about each driving aid in detail. Prior to the start of the experimental drive, the participants completed a pre-driving questionnaire survey, which captured the participants' socio-demographic background, driving experience, and driving behavior. After each drive, the participants were required to complete a NASA Task Load Index survey (Hart and Staveland, 1988). Furthermore, at the end of the experiment, the participants filled out a post-driving survey including user acceptance, trust in the technology, and sensation-seeking behavior.

Figure 5. Design of the driving aids in the connected environment

3.4 Driving behavior indicators

A variety of driving behavior indicators was analyzed for examining the impact of the connected environment. More specifically, the effects of various driving aids on different key parameters, listed in Table 2, are investigated.

Table 2. List of key driving behavior indicators considered in this study

Driving aid	Traffic interactions	Parameter	Definition
Continuous	Car-following on two-lane two-way highway	Average space gap	The mean distance between the front bumper of SV and the rear bumper of LV on the current lane during car-following
		Average time headway	The mean elapsed time between the front of LV passing a fixed on a roadway and the front of SV passing the same point
		Time-to-collision	The time for SV to collide with the LV on the current lane
Lane-changing gap information	Mandatory and Discretionary lane-changings on four-lane two-way motorway	Deceleration required to avoid collision (Cooper and Ferguson, 1976)	Deceleration required to avoid collision (DRAC) is differential speed between FV and SV divided by closing time DRAC = $\frac{(V_{FV,t} - V_{SV,t})^2}{(X_{SV,t} - X_{FV,t}) - L_{FV,t}}$
		Frequency of drivers exceeding -3.35 m/s^2	The frequency for each driver exceeding the braking threshold of -3.35 m/s^2 is calculated during a discretionary lane-changing event
Warning	Driving along Single lane, two-lane motorway, and city	Total number of warnings	The summation of the total number of warning per participant when a participant exceeded the posted limit speed for the designed roadway
Advanced advisory	Interactions with pedestrian and traffic lights in the city	Time-to-collision	The time for SV to collide with the pedestrian if they both continue their current state
		Running the yellow light	Frequency of the running the yellow light at a signalized interaction

To compare and analyze the impact of various driving aids on different driving behaviors, various statistical analyses like linear mixed model, paired *t*-test, chi-square, and non-parametric Wilcoxon tests were conducted. The confidence level was assumed as 95% for these statistical analyses.

4. Results

To analyze the driving performance among four drives, 78, 78, 74, and 73 trajectories were respectively obtained and evaluated for the baseline, perfect communication, communication delay, and communication loss conditions. Note that due to the imbalanced nature of data, a linear mixed model was utilized to examine the difference within and across subjects of correlated data since it has the capability to handle a dataset with missing observations (Haque et al., 2016). Ensuing subsection explains the impact of each driving aid on driving behavior.

4.1 Continuous driving aids

Table 3 shows the impact of continuous driving aids on car-following behavior behind the lead vehicle with 40 km/h speed, measured in terms of average space gaps, average time headway, and time-to-collision (TTC). Note that low-speed car-following only occurred in baseline and perfect communication (Table 1). During the low-speed car-following, the mean space gaps in the baseline and connected environment (i.e. connected environment with perfect communication) scenarios were respectively 31.12 m and 39.56 m. A paired *t*-test revealed that the participants maintained about 8 m higher space gap in the connected environment compared to the baseline condition; this difference was found to be statistically significant ($p < 0.001$). Meanwhile, the mean time headway in the connected environment was about 1.2 s longer than that of the baseline condition, implying a higher safety margin in the connected environment. A paired *t*-test ($p = 0.004$) further confirmed that the mean time headway was significantly different. Moreover, a longer and statistically different TTC was witnessed in the connected environment compared to the baseline scenario, further underscoring that the connected environment enhances traffic safety.

For the high-speed car-following, i.e., the lead vehicle was traveling at 85 km/h along the motorway with the posted speed limit of 100 km/h; note that high-speed car-following occurred in the baseline, perfect communication, and communication loss scenario (Table 1). The mean space gaps in the baseline, perfect communication, and communication loss scenarios were respectively 115.76 m, 111.98 m, and 42.91 m. The difference in mean space gaps was statistically different across three scenarios, as measured by the linear mixed model (*F-value* = 114.27, $p < 0.001$). Paired *t*-tests revealed no statistically significant difference between the spacing values in baseline and perfect communication scenarios ($p = 0.39$), but the differences in spacing values between baseline and communication loss scenarios ($p < 0.001$), and between perfect communication and communication loss scenarios ($p < 0.001$) were statistically significant.

Table 3. Effects of continuous driving aids on car-following behavior

Car-following section	Car-following elements	Mean (SD)			Significance *p*-value
		Baseline	PC	CL	
Low-speed	Average Space gaps (m)	31.12 (14.82)	39.56 (19.82)	-	Paired *t*-test: <0.001
	Average time headway (s)	6.07 (3.31)	7.27 (3.26)	-	Paired *t*-test: 0.004
	Minimum TTC (s)	3.82 (2.11)	8.94 (5.19)	-	Paired *t*-test: <0.001
High-speed	Average Space gaps (m)	115.76 (56.41)	111.98 (49.52)	42.91 (1.61)	Linear mixed model: <0.001
	Average time headway (s)	7.75 (3.28)	8.24 (3.13)	8.56 (1.52)	Linear mixed model: 0.511
	Minimum TTC (s)	3.55 (2.44)	7.33 (4.87)	4.73 (2.41)	Linear mixed model: <0.001

PC: perfect communication; CL: communication loss

Meanwhile, the mean time headways in the baseline, perfect communication, and communication loss scenarios were respectively 7.75 s, 8.24 s, and 8.56 s. The difference in mean time headways was not statistically different across three scenarios, as measured by the linear mixed model. Paired *t*-tests revealed no statistically significant difference in time headways between baseline and perfect communication scenarios ($p = 0.092$), nor between baseline and communication loss scenarios ($p = 0.601$), and perfect communication and communication loss scenarios ($p = 0.615$).

The mean minimum TTC in the baseline, perfect communication, and communication loss scenarios were respectively 3.55 s, 7.33 s, and 4.73 s. The difference in mean minimum TTC was statistically different across three scenarios as measured by the linear mixed model (*F-value* = 39.16, $p < 0.001$). Paired *t*-tests revealed a statistically significant difference in TTC values between baseline and perfect communication scenarios ($p < 0.001$), between baseline and communication loss scenarios ($p < 0.004$), and between perfect communication and communication loss scenarios ($p < 0.001$).

4.2 Event-based information

4.2.1 Driving aids for speed limit exceedance warning and tailgating warning

The effect of warning driving aids for the posted limit exceedance was analyzed across road traffic environments with various posted limits. The speed warnings were calculated at every 2 s, a typical reaction time value considered in the Australian standards (AUSTROADS, 1993). The total frequencies of speed warnings in the baseline condition for the two-lane two-way highway, four-lane two-way motorway, and the city environment were respectively 1479, 152, and 752 (Table 4). The corresponding frequencies in the connected environment (perfect communication) scenarios were respectively 1373, 4, and 384. A non-parametric test, in the form Wilcoxon test, was employed to compare the frequencies between two drives, and results indicated that the differences in speed warning frequencies between the baseline and perfect communication scenarios for each of the road traffic environment were statistically significant, as reported in Table 4 (Two-lane two-way highway: $p < 0.001$; Four-lane two-way motorway: $p < 0.001$; and city: $p = 0.004$).

Table 4. Impact of driving aid for the speed limit exceedance warning on the frequency of exceeding the posted speed limit

Sum of the frequency of exceeding the posted speed limit	Baseline	Connected Environment	Wilcoxon test
Two-lane two-way highway (posted speed limit 100 km/h)	1479	1373	<0.001
Four-lane two-way motorway (posted speed limit 100 km/h)	152	4	<0.001
City (posted speed limit 40 km/h)	763	384	0.004

Figure 6 shows speed warnings per participant across various road traffic environments. For two-lane two-way highway, about 74 drivers in the baseline condition have received more than five speed warnings throughout the drive, whereas 75 participants in the perfect communication scenarios have received less than five speed warnings. A similar trend was observed for the four-lane two-way motorway and city environment. These results clearly indicate that the connected environment helps drivers adapting their driver behavior towards safer driving. These results are consistent with previous studies (Brookhuis and De Waard, 1997, Brookhuis and de Waard, 1999, Lahrmann et al., 2001, Adell et al., 2011), reporting that drivers assisted with speed advisory systems (audio, visual, or both) were associated with less speeding behavior.

The effect of tailgating warning was analyzed for the car-following scenarios. Similar to the speed warning, the tailgating warnings were calculated at every 2 s. The total frequencies of tailgating warning in the baseline and the perfect communication scenario were respectively

76 and 77. The Wilcoxon test results indicated that tailgating frequencies between the baseline and perfect communication scenarios were not statistically different (p = 0.937).

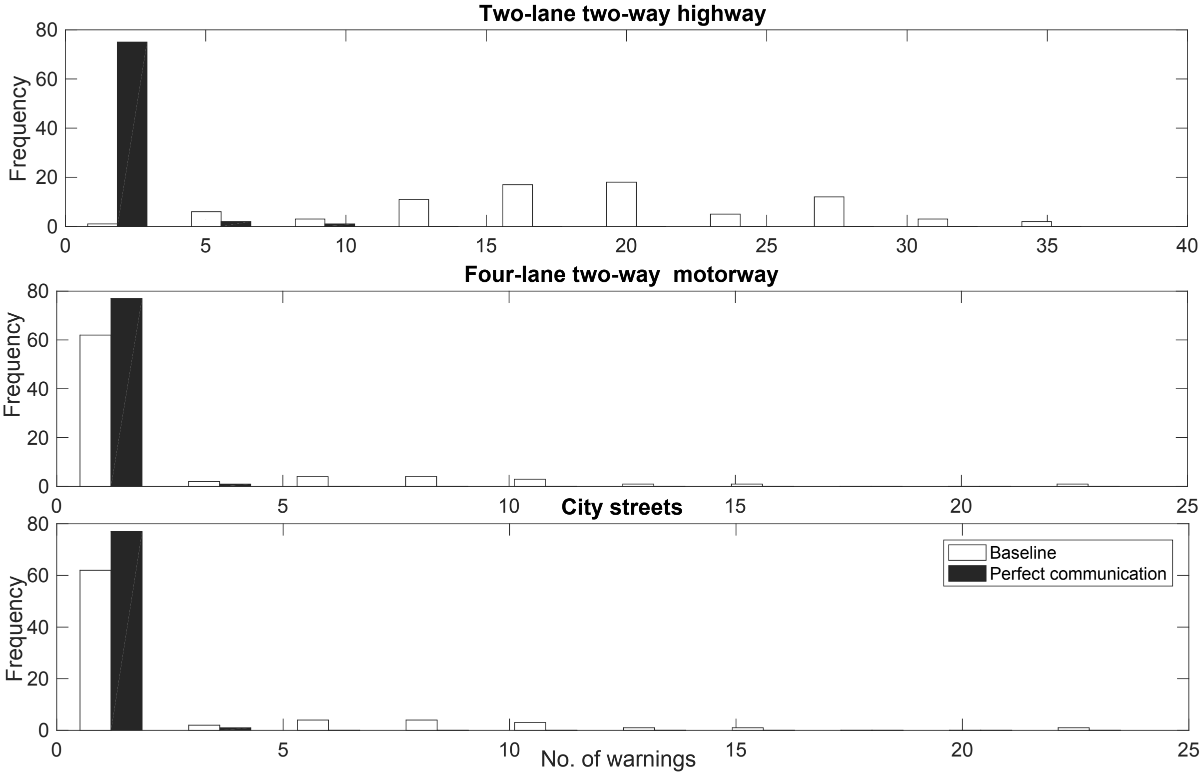


Figure 6. Speed limit exceedance warnings per participant across three road traffic environments

4.2.2 Lane-changing driving aids

Mandatory and discretionary lane-changing interactions were programmed along the four-lane two-way motorway where drivers in the former were required to leave the current driving lane while in the latter, drivers changed lanes to gain the speed advantage because the current driving lane was congested. In the literature, improper and risky lane-changing decisions are reported to be associated with sideswipe and rear-end collisions (Jun et al., 2007, Pande and Abdel-Aty, 2006). To decrease the workload and minimize judgment errors during lane-changing decision-making, the connected environment provided the information of the subsequent gaps available in the adjacent lane. Thus, to investigate the impact of the connected environment on safety associated with lane-changing maneuvers, a surrogate measure of safety (that is, deceleration required to avoid the crash, DRAC) was calculated during lane-changing events. Table 5 presents the DRACs calculated for both mandatory and discretionary lane-changings. Note DRAC was calculated when SV changed the lane. A higher DRAC rate indicates a higher risk.

For mandatory lane-changing, the mean DRACs for the baseline, perfect communication, and communication delay scenarios were -5.75 m/s^2, -3.1 m/s^2 and -3.95 m/s^2, respectively (Table 5). DRACs were about 2.65 m/s^2 and 1.80 m/s^2 higher in the baseline condition compared to the perfect communication and communication delay scenarios, respectively, suggesting a lower crash risk in the connected environment. The overall difference in DRACs measured by the linear mixed model was found to be statistically significant, as reported in Table 5. The differences in DRACs between the baseline and the connected environment as well as between baseline and communication delay scenarios were also found to be statistically different by paired *t*-tests.

Table 5. Impact of lane-changing driving aid on safety during the lane-changing events

Surrogate measures of safety	Baseline [Mean (SD)]		Connected Environment [Mean (SD)]						Significance	
			PC		CD		CL			
	MLC	DLC	MLC	DLC	MLC	DLC	MLC	DLC	MLC	DLC
DRAC, m/s²	-5.75 (2.43)	-5.11 (1.76)	-3.1 (1.18)	-3.35 (0.95)	-5.25 (2.11)	-3.95 (1.55)	-	-4.31 (1.83)	Linear mixed model: <0.001	Linear mixed model: <0.001
Frequency of drivers exceeding -3.35 m/s²	20	17	6	5	12	10	-	15	Chi-square test: <0.001	Chi-square test: <0.001

MLC: mandatory lane-changing; DLC: discretionary lane-changing; PC: perfect communication; CD: communication delay; CL: communication loss

The mean DRACs for the baseline, perfect communication, communication delay, and communication loss scenarios during the discretionary lane-changing event were respectively -5.11 m/s², -3.35 m/s², -3.95 m/s², and -4.31 m/s². The differences in DRACs were found to be statistically different across four drives as measured by the linear mixed model. Paired *t*-tests further revealed that the DRACs in the baseline condition was significantly different from the perfect communication, and communication delay scenarios (p <0.001). More specifically, the DRACs in the perfect communication, communication delay, and communication loss scenarios were about 1.76 m/s², 1.16 m/s², and 0.8 m/s², respectively, lower than that of the baseline condition, implying that the connected environment provided a higher safety margin during the discretionary lane-changing event.

Archer (2004) suggested that a vehicle is considered to be engaged in a traffic conflict if its DRAC exceeds a threshold braking value of -3.35 m/s². Thus, the frequencies of the participants exceeding this threshold were calculated for both mandatory and discretionary lane-changings. During the mandatory lane-changing event, 20, 6, and 12 participants respectively required a DRAC greater than- 3.35 m/s² in the baseline, perfect communication, and communication delay scenarios (Table 5). This difference between these frequencies was found to statistically different, as indicated by the chi-square test (p <0.001). Table 5 also shows that during discretionary lane-changing, 17 participants in the baseline condition required a DRAC higher than -3.35 m/s² while the corresponding frequencies in the perfect communication, communication delay, and communication loss scenarios were 5, 10, and 15. The differences in these frequencies across driving conditions, as tested by the chi-square test, were found to be statistically significant (p <0.001). These results suggest that the connected environment improves safety around lane-changing maneuvers as drivers in the connected environment are found to be less engaged in traffic conflicts measured by DRAC in this study.

4.2.3 Advanced advisory driving aids

The participants in the perfect communication scenario received advanced advisory information on upcoming situations to provide additional time to handle and react to the situation. Two advanced driving aids included in this driving simulator experiment were a traffic light change at signalized intersections and pedestrians' presence on the zebra crossings. From the traffic light change scenario (refer to Figure 5(c)), the frequency of running the yellow light was calculated. Table 6 shows the frequency of running the yellow light, and it can be observed the frequency of running the yellow light in the baseline condition was about twice that of the perfect communication scenario; the chi-square test showed that the frequencies were statistically different (p <0.001). This result indicates that drivers are more cautious in the perfect communication scenario compared to the baseline condition, and the connected environment helps drivers to comply with the traffic lights more often.

Table 6. Impact of advanced advisory driving aids during traffic interactions in the city road traffic environment

City events	Baseline	Perfect communication	Significance
Yellow light running frequencies at the signalized intersection	51	27	Chi-square test: <0.001
Time to collision to the pedestrian at the start of the braking point [s, (SD)]	4.70 (0.69)	4.90 (0.49)	Paired *t*-test: 0.036

For the pedestrian scenario (Figure 5(c)), time-to-collision (TTC) to the pedestrian was calculated when a driver interacted with the pedestrian entered in a zebra crossing from the sidewalk. As reported in Table 6, the TTCs for the baseline and perfect communication scenarios were respectively 4.7 s and 4.9 s. A paired t-test showed that TTC was 0.2 s longer in the perfect communication scenario, and this difference was found to be statistically significant (p = 0.036). These results indicate that driving aids provided through vehicle-to-infrastructure communication in the connected environment improve safety margin for the interactions with pedestrians on a zebra crossing.

5. Discussion

To examine the effects of the connected environment on driving behavior and safety, this study has designed a large-scale driving simulator experiment to collect high-quality vehicle trajectory data along with human factor information. Participants performed various routine driving tasks, including car-following, lane-changing, interactions with traffic signals and interactions with a pedestrian on a zebra crossing, with and without the presence of the driving aids.

During the car-following scenarios, drivers in the connected environment were found to maintain larger space gaps and longer time headways compared to driving in the baseline condition. Previous studies have unanimously reported a similar conclusion for car-following behaviors with driver assistance systems. For instance, Wang et al. (2013) reported an increase in time headway when a longitudinal warning assistance system was provided compared to driving without the system. In an instrumented vehicle study, Birrell et al. (2014) assessed the benefits of smart aids for real-world driving and reported an increase of 2.3 s in mean time headway during car-following.

A slightly contrasting result has been observed for average space gaps while comparing the difference between baseline and connected environment conditions during the low-speed (lead vehicle speed 40 km/h) and high-speed (lead vehicle speed 85 km/h) car-following sections. Drivers maintained a higher space gap in the connected environment (perfect communication) compared to the baseline condition along the low-speed section, but no significant difference is observed along the high-speed section. Note that the average space gap along the low-speed section was around 30 m, whereas the average space gap along the high-speed section was around 112 m. It is quite obvious that drivers maintained higher space gaps during high-speed car-following mainly because they needed more space and time to react to any situation and control their vehicle safely (Loulizi et al., 2019). Given that drivers maintain high space gaps in the connected environment, no statistical difference in space gaps between the connected environment and baseline was observed during the high-speed car-following condition of this study.

Drivers in the connected environment were found to maintain longer TTCs, revealing a higher safety margin when drivers were assisted with driving aids compared to when they were driving without it. Similar findings are reported in the literature. For instance, Osman et al. (2015) analyzed the impact of communicating safety messages during the connected environment on driver behavior and found that aggressive drivers maintained a longer TTC during the drive with safety messages compared to the drive without messages. Recently, Sharma et al. (2019) examined the driver response time in the connected environment and found that the mean response time in the connected environment was longer than that of the traditional environment, implying enhanced safety in the connected environment.

Drivers were found to adjust their speed selection behavior when they received speed limit exceedance warning in the connected environment as the frequency of speed limit exceedance warnings was consistently lower in the connected environment compared to the baseline condition. Past studies have also reported that drivers comply to the posted speed limit when they were warned by in-vehicle information systems (Vashitz et al., 2008, Whitmire et al., 2011). Unlike speed exceedance warning, no significant difference has been observed for tailgating warning between the baseline and connected environment driving conditions. This finding contrasts the existing literature (De Waard and Brookhuis, 1997, Song and Wang, 2010) where drivers were reported to receive fewer tailgating warnings when they were informed about it. In the experiment of this study, drivers received continuous information about the distance from the leading vehicle, which may have led to follow the lead vehicle closely, resulted in the reduced effectiveness of tailgating warnings. In this study, warning aids were provided immediately after the critical event. However, there is a great need to understand and determine what is the best time to disseminate a warning message. Is it just immediately after the violation of speed limit or tailgating or after certain time interval? This design may have significant implications on the effectivness of connected environment. These questions need be thoroughly investigated before the deployment of connected vehicles in the real-world.

During lane-changing scenarios, drivers in the connected environment have been observed to maintain a higher safety margin. Previous studies have also reported that the lane-changing assistance system improves safety. For example, Jeong et al. (2014) utilized microsimulations to simulate driving behavior in the connected environment with warning messages and found that rear-end conflicts during lane-changing maneuvers reduce with an increase in the market penetration rate of warning message technology.

The advance advisory driving aid for the traffic light change at signalized intersections has also been found very effective, as drivers in the connected environment with this aid were found to be associated with fewer yellow light runnings. This result is consistent with past studies in the literature. For instance, Bar-Gera et al. (2013) reported that drivers assisted with a system of audio and visual information about stopping at a signal reduced red-light running violation by 96% compared to driving when the system was not available. Moreover, Yan et al. (2014) evaluated the effectiveness of an in-vehicle system on red-light running events at signalized intersections and reported smaller collision rates when driving with the system compared to that of without the system.

The advisory driving aid for the pedestrian's presence on a zebra crossing has also been found to be effective as drivers in the connected environment were found to maintain a longer TTC compared to drivers in the baseline condition without this driving aid. De Nicolao et al. (2007) have also reported that on-board sensors that generate a collision warning to a pedestrian were effective in reducing collision risk with pedestrians. De Boer et al. (2010) conducted an online questionnaire survey to understand the acceptance of pedestrian warning at intersections, and found a very positive response about the usefulness of pedestrian safety warning. In addition, Yue et al. (2018) proposed a combined framework for driving assistance with connected vehicle technology and reported that the framework has the capability to reduce the crashes for light vehicles and pedestrians.

The connected environment is expected to provide information via vehicle-to-vehicle communication and vehicle-to-infrastructure communication using sensors and LIDARS (Kim, 2015). In real-world, it is anticipated that information transfer may not work perfectly all the time due to various reasons. As such, in this study, three forms of the connected environment are utilized, namely perfect communication (uninterrupted supply of driving aids), communication delay (driving aids are delayed by 1.5 s), and communication loss (driving aids are intermittently lost). This study found that when driving aids were provided uninterruptedly, safety has been improved significantly, but it deteriorates when driving aids are delayed by 1.5 s. Notably, the effects of communication loss were even worse compared to no driving aids, as drivers may try to extract information from the connected environment when it was not there due to the communication loss.

6. Conclusions and Future research directions

This study examined the impact of various driving aids provided by the connected environment on driving behavior and safety. An innovative driving simulator experiment was designed, which consisted of car-following scenarios, lane-changing scenarios, interaction with a traffic signal and interaction with a pedestrian. Two types of driving aids, namely continuous and event-based driving aids, were provided in the connected environment. Furthermore, to realistically mimic situations that drivers may experience in the connected environment in the future, communication delay and communication loss scenarios were also considered in the experiment design. A range of driving behavior indicators for each of these scenarios have been compared between the baseline and connected environment conditions.

The impact of continuous driving aids was evaluated during car-following situations, in which drivers were provided with the information such as distance to and speed of the leader vehicle. Drivers in the connected environment were found to maintain a higher safety margin as they have been found to maintain a higher space gap and a higher time headway. The warning driving aid for exceeding the posted speed limit notified drivers whenever they exceeded the speed limit. This driving aid has been found to reduce over-speeding instances among the drivers in the connected environment.

The impact of lane-changing driving aid (another sub-class of event-based information) was examined by comparing the ‘deceleration required to avoid the crash’ during mandatory and discretionary lane-changing maneuvers. During the lane-changing decision-making process in the traditional environment, drivers only estimate the immediate following gap in the adjacent lane, which is visible by a naked eye. However, drivers are not aware of the subsequent gap information that could be useful in selecting an appropriate gap and reduce the crash risk associated with lane-changing. This study has found that when drivers receive the subsequent gap information in the connected environment, they tend to perform lane-change with a higher safety margin.

One of the noteworthy advantages of the connected environment is the provision of advanced advisory driving aids on upcoming and unseen situations in an urban context such as interacting with a pedestrian walking on a zebra crossing. Conventionally, drivers react to pedestrians when they are visible on the zebra crossing or sidewalk. In such a situation, drivers are often required to take evasive actions to avoid a collision with pedestrians, which can be detrimental. However, when drivers receive advanced information about pedestrians walking from the sidewalk, they tend to be more prepared to give way and maintain a higher safety margin. The advanced advisory driving aid at the onset of yellow light has also been found to have a positive effect on safety as it is associated with the lower propensity of yellow light running at signalized intersections.

Overall, the connected environment has been found to improve driving behavior towards safety.Whilst the findings of this study demonstrate a very promising effect of the connected environment as a whole, this study demonstrates that the benefits of the connected environment are maximum when the communication is perfect. Any impairment in the connected environment such as communication delay and communication loss are likely to deteriorate safety compared to the perfect communication scenario.

This study investigated the effects of communication impairments such as communication delay and communication loss only on particular driving aids and driving events. A worthwhile research direction would be investigating the effects of communication impairments across various types of driving aids and road traffic interactions. Furthermore, driving aids were disseminated on the windscreen similar to Heads-up display, however, latest vehicle technologies are using a big screen (like IPad) to share information to drivers. Thus, it is worth investigating the differential behavior, if any, using different information dissemination systems and find the best way to transfer driving aids to drivers. An associated research avenue could be examining the potential distraction caused by the system and its negative impact on driving behavior.

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