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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 assistance, lane-changing support, 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 communication 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 a 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 diverse backgrounds 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). Various 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 scenario 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.

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

In 2017, the National Highway Traffic Safety Administration (NHTSA) in the U.S reported 2.77 million vehicle crashes that caused 1.68 million passenger injuries and damaged 4.5 million vehicles, and 94 % of these crashes were associated with human errors (NHTSA, 2017). More specifically, 17.8 % of the 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 the crashes involved drivers disobeying the traffic rules such as traffic signals.

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

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Table 1
Summary of representative studies related to the impact of driving assistance systems and connected environment on driving behavior.

Study	Methodology	Event	Information disseminated	Findings
Driving assistance studies				
May et al. (1995)	Field experiment	Car following	Time headway	Decreased time headway
Fairclough et al. (1997)	Field experiment	Car following	Time headway	Increased time headway
Groeger (1998)	Field experiment	Car following	Time headway	Increased time headway
Comte and Jamson (2000)	Driving simulator	Car following	Speed, acceleration, and lateral position	Reduced speed
Lee et al. (2002)	Driving simulator	Car following	Time headway and deceleration	A fewer number of collisions
Ben-Yaacov et al. (2002)	Field experiment	Car following	Time headway	Decreased time headway
Maltz and Shinar (2007)	Driving simulator	Car following	Time headway	Increased time headway
Erke et al. (2007)	Field experiment	Car following	Route choice, speed, and braking behavior	Large speed reductions
Adell et al. (2011)	Field experiment	Car following	Safe speed and safe distance (headway)	Reduced number of alarms, shorter alarm lengths, shorter reaction times, increased headway
Saffarian et al. (2013)	Driving simulator	Car following	lead-car acceleration and time headway	Decreased time headway
Ghadiri et al. (2013)	Field experiment	Car following	Intelligent Speed activation	Reduced average speed
Connected environment studies				
Caird et al. (2008)	Driving simulator	Intersection	Advanced in-vehicle signs	Slower approaching speed and reduced yellow light running
Sugimoto et al. (2008)	Simulation	Pedestrian	Warning	Reduced collisions rates
Dotzauer et al. (2013)	Driving simulator	Intersection	Intersection assistance	Crossed intersections more often in a shorter time with higher speeds
Birrell et al. (2014)	Field experiment	Car following	Headway, lane departure, gear change, acceleration, and braking	Increased headway and reduced tailgating
Guler et al. (2014)	Simulation	Intersection	NA	Reduced the average delay
Liu and Khattak (2016)	Field experiment	Car following	Instantaneous feedback and control assistance	Identified extreme events
Bakhit et al. (2017)	Field study (but traditional data)	Lane-changing	Detecting the onset of lane change maneuvers	Early predictions of drivers; intentions
He et al. (2017)	Simulation	Pedestrian	NA	Improved pedestrian protection
Tang et al. (2017)	Simulation	Traffic signal	Remaining green time	Improved safety at intersections
Tahmasbi-Sarvestani et al. (2017)	Simulation	Pedestrian	Situational awareness and hazard detection	Smoother braking behavior
Kang et al. (2018)	Simulation	Lane-changing	Optimal lane selection	Decreased travel time
Abdulsattar et al. (2018)	Simulation	Work zone	Speed limit and distance	Enhanced safety
Rahman and Abdel-Aty (2018)	Simulation	Platooning	Joining strategies	Improved safety
Xu et al. (2018)	Simulation	Pedestrian	Smart road sticker	Conflicts increases with a decrease in the market penetration rate of connected vehicles
Chang et al. (2019)	Driving simulator + simulation	Car-following	Speed recommendation, front distance, and speed limit	A positive impact on speed, front distance, and the time to a stable regime
Zhao et al. (2019)	Field	Pedestrian	NA	Early detection of pedestrian intentions
Hong et al. (2020)	Simulation	Car-following	Safety score	Improved the overall performance of the traffic system
Payre and Diels (2020)	Driving simulator	Car-following	Emergency electronic brake lights, emergency vehicle warning, roadworks warning, and traffic condition warning	Shorter braking and decelerating response time

NA: studies do not mention which type of information was disseminated.

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, thereby 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, and obeying traffic signs and lights in urban situations. 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 leading vehicle suddenly brakes.

To this end, a connected environment provides various driving aids through informatory messages and/or warnings 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 maneuvers (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 to 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 process and comprehend the high amount of information from a connected environment, and thereby can deteriorate their driving performances (Strayer et al., 2019). However, there is no concrete evidence of such negative impacts of a connected environment on driving behavior. Now the questions arise: can drivers improve their decisions and react to the information from a connected environment effectively? Or, will drivers be misled by a 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 the 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 the success of a 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 a 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 a connected environment on driving behavior and safety. To achieve this objective, an innovative driving simulator experiment was designed considering various routine driving tasks in a 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.

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 tasks. Finally, Section 6 summarizes the main conclusions and suggests future research directions.

2. Literature review

Table 1 summarizes representative studies from the literature on driving assistance systems and connected environment. A thorough literature review reflects that various driving tasks have been analyzed, including car-following, lane-changing, and interactions with pedestrians and signalized intersections. As this study examines the impact of the connected environment on various driving tasks, this literature review section is divided into five subsections based on driving tasks, namely car-following behavior in a connected environment, lane-changing behavior in a connected environment, infrastructure-to-vehicle interactions in a connected environment, macroscopic benefits of a connected environment, and field studies on a connected environment. The last subsection summarizes the findings from the existing literature, identifies the research gap, and highlights the contribution of this study

2.1. Car-following behavior in a connected environment

Connected vehicles are designed to provide assistance to drivers to safely perform various routine driving tasks. For car-following scenarios, Chen et al. (2005) quantified the safety benefits of in-vehicle information systems and found that the crash rates with and without the system were respectively 0.06 and 0.12. 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 present. 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 a 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 decreased 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 in avoiding hard decelerations and maintaining a safe headway, proper lane positions, and small lane deviations.

2.2. Lane-changing behavior in a connected environment

Lane-changing, a lateral and one of the complex driving tasks that require surrounding 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) or to achieve better driving conditions (i.e., discretionary lane-changing). Inaccurate and risky lane-changing decisions are reported to deteriorate traffic safety. In particular, lane-changing is associated with rear-end and sideswipe crashes with the follower in the target lane (Sen et al., 2003). In 2018, lane changing maneuvers were reported to result in about 2530 and 827 rear-end and sideswipe collisions, respectively, in New South Wales, Australia (TfNSW, 2019). Similarly, Zheng et al. (2010) reported that traffic disturbance (i.e., traffic oscillations caused by lane-changing) on freeways could significantly increase drivers' likelihood of getting involved in crashes. 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. Infrastructure-to-vehicle interactions in a connected environment

The aforementioned studies mainly describe car-following and lane-changing on a motorway. On the other hand, driving in an urban environment, which involves interactions with traffic lights and various road users like pedestrians and cyclists, is often a demanding task. 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 messages on brake response time to a red-light running and found that an auditory warning message significantly reduced braking time and collision occurrence rate. In a microsimulation platform, Njobelo et al. (2018) tested an advanced stop assist system for signalized intersections. They found 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 collisions with a pedestrian reduced drastically, when the system was activated.

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

Since a connected environment is not currently operating at a large scale, past studies have mainly reported various benefits of a connected environment using numerical simulations. Olia et al. (2016), for example, developed a modeling framework based on microsimulation for connected vehicles (vehicles operating in a connected environment) and reported that these vehicles improved traffic efficiency, enhanced safety, and reduced greenhouse gas emissions at the 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 a 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 eliminated the need for a traffic signal at intersections. This microsimulation 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 a connected environment, Ahmed et al. (2017) showed that drivers with the system could collaborate and safely merge to a freeway.

2.5. Field studies on a connected environment

The Connected Vehicle Safety Pilot Model Deployment Program is one of the first field tests on connected vehicle driving environment, which was initiated by the University of Michigan Transportation Research Institute in collaboration with USDOT (Narla, 2013). Using the instrumented vehicles and utilizing vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, messages were disseminated for different traffic scenarios such as an impending collision at a blind intersection, a vehicle changing lanes in another vehicle's blind spot, and a potential rear-end collision with a stopped vehicle. Using the data obtained from this project, a study developed a logistic model that could predict risky behavior of drivers at the point of curvature on horizontal curves (Ghanipoor Machiani et al., 2017). While realizing the predictive capability of this model, it was concluded that the developed model could be used to activate smart curve speed warnings in a connected environment (Ghanipoor Machiani et al., 2017). Zhang et al. (2017) utilized the same data obtained from the connected vehicle safety program and developed a real-time collision warning system based on time-to-collision. Similarly, Hayat et al. (2014) tested a freeway merge assistance system and reported that drivers complied with the provided information and selected the largest gap size and thereby reduced crash risk. Using the same testbed, Rakha et al. (2016) tested eco-speed control in a connected environment and found stable driving behavior near intersections, thereby reducing fuel consumption levels and travel times. In another study, Linton and Fu (2016) developed machine learning models that could predict road surface conditions during the winter season so that drivers can be informed through a connected vehicle environment system. The developed models showed higher accuracy in predicting different states of road surfaces. Doecke et al. (2015) used the data from the in-depth crash investigations by the Centre for Automotive Safety Research in South Australia and reported that vehicle crashes could be significantly reduced in a connected environment. Farah et al. (2012) investigated the impact of the CO-OPerative SystEms for Intelligent Road Safety (COOPERS), which are based on infrastructure-to-vehicle (I2V) communication, on driving behavior. A total of 35 participants drove the instrumented vehicle. The disseminated safety messages were speed advice, upstream accident advice, road conditions ahead, lane-keeping advice, and speed limit advice. They reported no statistically significant difference in the acceleration noise when the I2V communication was available versus when it was unavailable. Note that V2V communication and the corresponding messages such as the speed of and spacing to the leader were not included this system.

2.6. Research gap and contribution of this study

The synthesis of the literature reveals that (i) early efforts were related to driver assistance systems, which mainly utilized sensors and LIDARS and analyzed the impact of various driving aids discretely; (ii) more recent efforts focused on the impact of a connected environment at macroscopic (or network-wide) level, and consequently mostly reported macroscopic benefits of the connected environment; (iii) while some studies on driver assistance systems were conducted in field and driving simulator environments, most of the connected environment studies were mainly performed through numerical simulations; and (iv) while the majority of the studies analyzed car-following task, other routine driving tasks such as lane-changing, interaction with traffic signals, and interaction with pedestrians have not received much attention. In summary, our understanding remains elusive on how a connected environment influences driving behavior and safety, and what and how driving aids should be disseminated. In other words, a detailed and holistic microscopic investigation of connected environment's impact on routine driving tasks is missing, which is critical for the success of a connected environment. This research gap motivates the present study.

This study contributes to the literature by designing and conducting a large-scale driving simulator experiment to collect high-quality vehicle trajectory data for a novel connected environment. Unlike the existing studies where driving aids are discretely analyzed, drivers are continuously assisted with different driving aids using V2V and V2I information during various vehicular interactions such as car-following, lane-changing, and interactions with a traffic signal at signalized

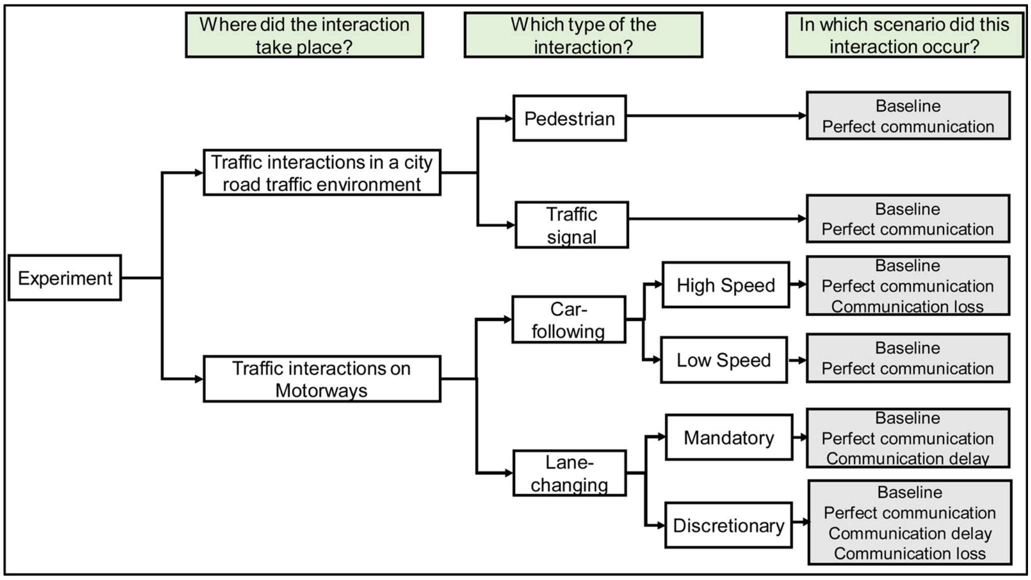

Fig. 1. Driving conditions and traffic interactions designed for the driving simulator experiment.

intersections and pedestrian crossings. Moreover, unlike most of the similar studies in the literature, a set of questionnaires is also carefully designed and included as part of the driving simulator experiment to gauge human factors' role in connected environment's impact on driving behavior, e.g., a pre-driving questionnaire survey for obtaining information related participants' socio-demographic background, driving experience, and driving behavior; a motion sickness assessment questionnaire during the experiment; a post-driving study including user acceptance, trust in the technology, and sensation-seeking behavior.

3. Experimental design and data collection

Due to the novelty of a connected environment and the scarcity of relevant data, an innovative driving simulator experiment was designed to collect high-quality vehicle trajectory data for a connected environment using the Centre for Accident Research and Road Safety-Queensland (CARRS-Q) Advanced Driving Simulator. Fig. 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. Each participant was asked to drive in all four scenarios ensuring similar distribution of participant characteristics in the experiment. The driving simulator experiment included traffic interactions on motorways and in urban 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 urban environment included interactions with a traffic light change at signalized interactions and interactions with a pedestrian at pedestrian crossings. The durations of traffic interactions in the urban environment were short (more information on this is provided in later sections), and thus, it was not possible to simulate communication delay and communication loss scenarios in the simulator for these interactions. 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 is provided in the ensuing subsections.

3.1. Advanced driving simulator

The simulator consists of a fully functioning Holden Commodore car and three front-view projectors, providing a 180° field of view. To mimic real-life driving and vehicle interaction with road features, the simulator car was fixed to 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 frequency of 60 Hz, and the advisory and trajectory data were collected from the advanced driving simulator at a frequency 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 and 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 licence. 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 a city road traffic environment. The entire road geometry is presented in Fig. 2, where different road sections, and various traffic events and vehicular interactions are numbered. The motorway section was divided into two parts: a two-lane two-way highway and a 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 a two-lane two-way highway via an on-ramp, and the scenario ended soon after merging to the highway (Fig. 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) 3 km long highway (Section 1 in Fig. 2) was designed for the car-following scenario where the participants followed a platoon of vehicles. The

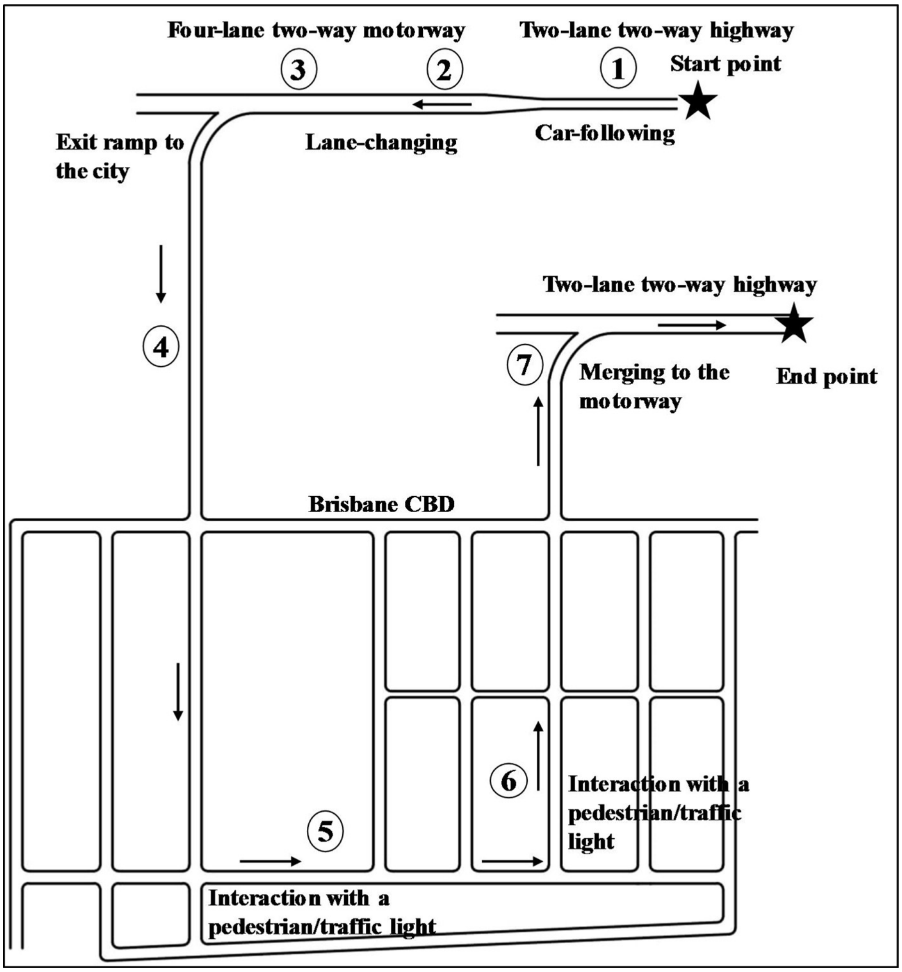

Fig. 2. Schematic diagram of the experiment route (not in scale).

programmed leading cars (LVs hereafter) followed the pre-specified speed profile, as shown in Fig. 3, whereas the participants' car-following behavior was at their discretion. It can be observed in Fig. 3 that two speed profiles were designed for two car-following sections, namely high-speed car-following and low-speed car-following.

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. The lead vehicle (LV) accelerated at a rate of 1.5 m/s^2 until it attained the speed of 85 km/h (i.e., desired speed) 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. The naturalistic studies have reported that this deceleration rate is associated with safety-critical events (Wu and Jovanis, 2013). The LV then came to a standstill position and maintained this 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 the two-lane two-way highway was connected to the four-lane two-way (two lanes in each direction) motorway, where programmed vehicles were waiting for the subject vehicle for lane-changing 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 length was allocated for the two lane-changing scenarios. In the first section (Section 2 in Fig. 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 (Fig. 4(a)). The following vehicles (FVs hereafter) in the target lane (L_1) created five mandatory lane-changing gaps ranging from 15 m to 90 m. Several studies have suggested that a lane-changer and its immediate follower interact with each other when the gap between them is about 60 m or less (Toledo et al., 2003; Liu et al., 2007). Following this suggestion, gap sizes were provided at a regular interval in the target lane. SV can select any gap from the available gaps and enter 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 Fig. 2 and Fig. 4(b)), the LV started moving slowly in front of SV in L_2. Meanwhile, FVs in the target lane (L_1) were moving at 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 the simulated Brisbane CBD area. To realistically represent the surrounding environment of Brisbane CBD, a detailed simulation of Brisbane CBD with a great deal of accuracy was carried out. The posted speed limit in

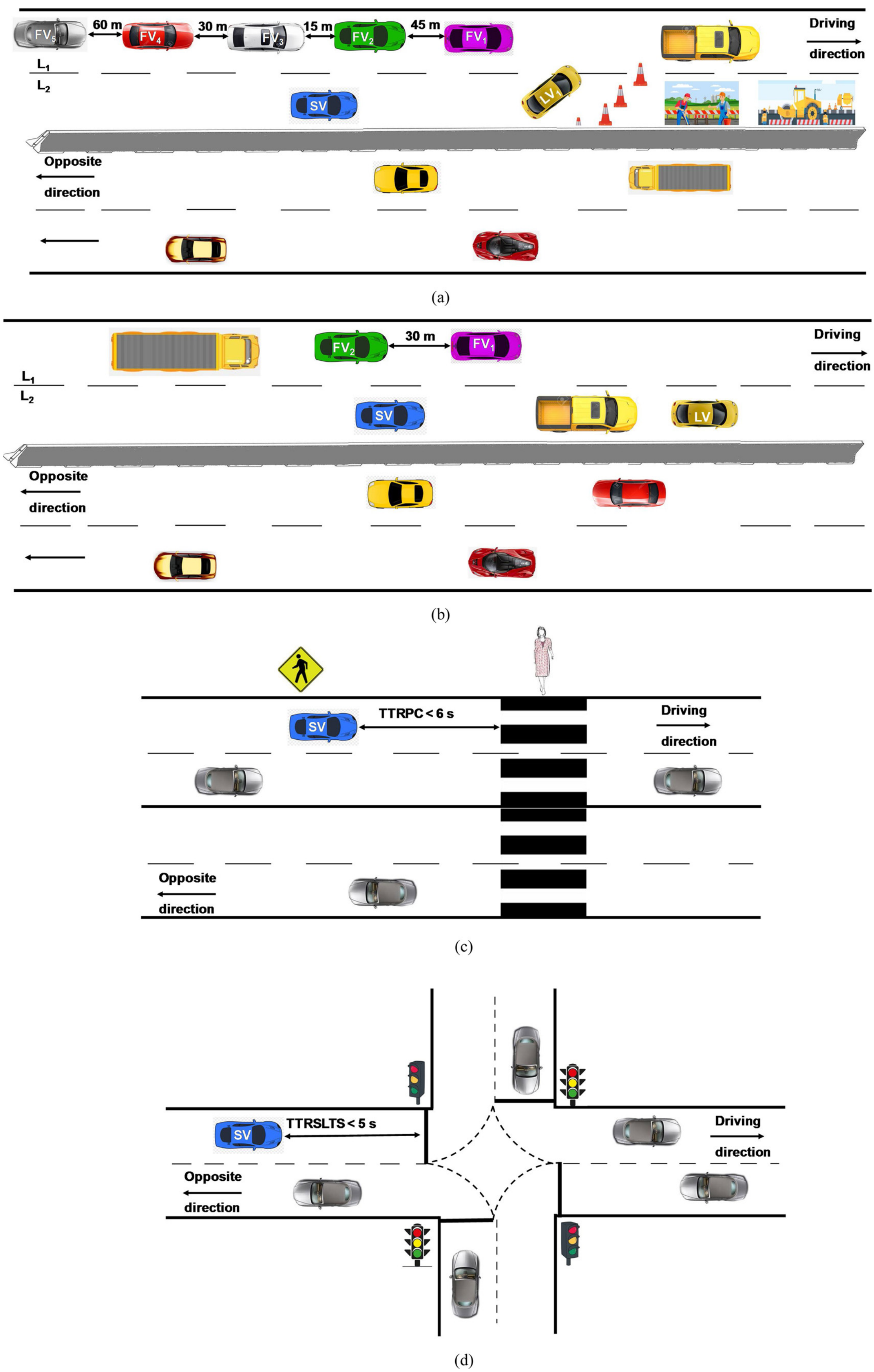

Fig. 3. Vehicular interactions during: (a) mandatory lane-changing; (Section 2 of Fig. 2) (b) discretionary lane-changing (Section 3 of Fig. 2); (c) Time-to-reach pedestrian crossing (TTRPC) (Section 4 of Fig. 2); and (d) Time to reach stop line at the traffic light (TTRSLTS) (Section 5 of Fig. 2).

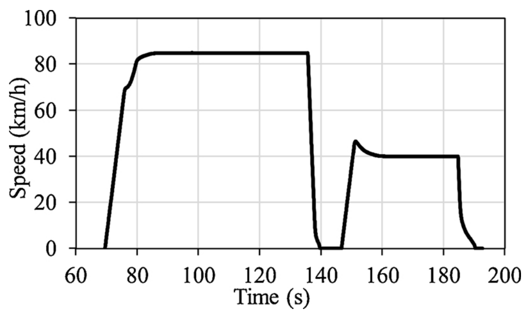

Fig. 4. A typical speed profile of the leading car in the car-following scenario (along Section 1 of Fig. 2).

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 Fig. 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 (Fig. 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 interaction with a pedestrian, where a driver needed to respond to a pedestrian entering a pedestrian crossing from the sidewalk, as shown in Fig. 4(c). The pedestrian (zebra) crossing and traffic sign were placed as per 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 (randomly chosen) 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 turn to enter Section 6 (Fig. 2), where the second event in the city occurred, i.e., a traffic light turning red from green. In this event, the driver had to decide whether to stop or run the yellow light (Fig. 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 surrounding traffic 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 modern vehicle models.

In the connected environment, two types of driving messages were disseminated, including continuous and event-based information. Continuous information (Fig. 5(a)) was continuously presented on the bottom left corner of the windscreen, informing about the driving conditions in the current lane, i.e., the speed of and the distance to LV in the current lane. Event-based driving messages appear depending on the occurrence of events. These messages included warnings for safety-critical situations, lane-changing messages, and advisory information about upcoming traffic interactions. A warning message with a beep sound appeared during safety-critical situations like exceeding the posted speed limit and driving too close to LV, i.e., tailgating warning. When a participant exceeded the posted speed limit (Fig. 5(a)), a speed limit sign flashed up with a beep sound. Similarly, when a participant drove too close to LV (TTC ≤ 1.5 s) in the current lane, the spacing sign flashed out with a beep sound. This threshold has been reported to be associated with a high risk of collision during car-following situations (Van Der Horst and Hogema, 1993; Lee et al., 2002; Vogel, 2003). Meanwhile, when a lane-changing opportunity is available in the adjacent lane, a lane-change message (Fig. 5(b)) popped up on the left corner of the windscreen. The blue and red cars (Fig. 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 (Fig. 5(c)) and pedestrians' presence on the zebra crossings (Fig. 5(c)). The advanced information about the change in traffic light was provided when SV was 5 s away from the stop line following the standard traffic signal design in Queensland, Australia (DTMR, 2017), where the yellow (or amber) interval is generally 3 s. Allowing 2 s for drivers to read and interpret the message 'Red light in 5 s', this threshold was set to 5 s. 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. This threshold was selected in accordance with the Austroads guidelines (AUSTROADS, 1993). The desirable stopping sight distance along a road with the speed limit of 40 km/h (note that the speed limit was 40 km/h in CBD section of our experiment) is 45 m. In other words, a driver driving at a speed of 40 km/h will require approximately 4 s to stop. Considering that a driver may require 2 s in reading and interpreting the message, this threshold was conservatively set to 6 s.

Note that the advanced advisory messages were presented in yellow text (consisting of three to five words) at the bottom of the windscreen along with a beep sound to alert the participants. All of these messages were provided well in advance to the occurrence of a particular event. For instance, when the time to reach pedestrian crossing was less than 6 s (and the pedestrian had not actually started walking from the sidewalk), the message was disseminated. 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 this delay on traffic safety. In the communication loss scenario, the participants received information on a certain segment of the motorway (e.g., low-speed car-following and mandatory lane-changing), but for another (subsequent) segment (e.g., high-speed car-following and discretionary lane-changing), the information was unavailable.

In this study, each participant drove along the motorway as well as in the urban environment (Brisbane CBD), where different vehicular interactions were designed (see Table 1 for description). During the baseline and perfect communication driving conditions, each participant faced all of the interactions along the motorway and in the urban environment reported in Table 2. During the communication delay and communication loss driving conditions, the participant only drove on the motorway and faced car-following and lane-changing events. A complete list of traffic interactions across four driving conditions is shown in Table 2.

The suitability and associated workload of driving aids were carefully tested and examined during a pilot testing. The NASA Task Load

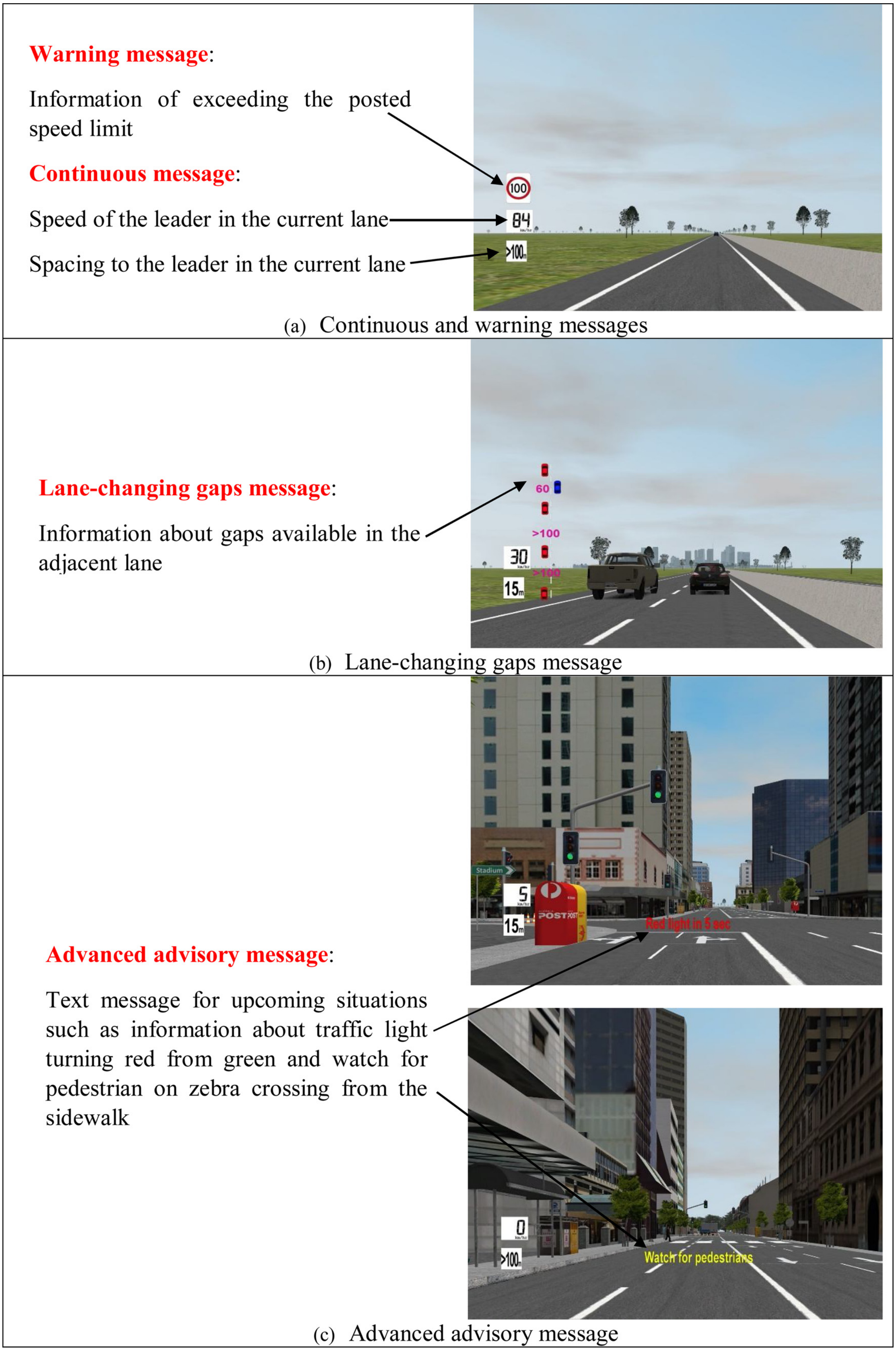

Fig. 5. Design of the driving aids in the connected environment.

Table 2
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.

Table 3
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 spacing	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 point on a roadway and the front of SV passing the same point
		Time-to-collision	The time required for SV to collide with LV if they continue at their present speeds and on the same path in 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 the differential speed between FV and SV divided by closing time $\mathrm{DRAC} = \frac{(v_{FV,t} - v_{SV,t})^2}{(x_{SV,t} - x_{FV,t}) - L_{FV,t}}$
		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
		Maximum deceleration	The maximum deceleration observed in each scenario
Warning	Driving along single lane, two-lane motorway, and in city roads	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 running the yellow light at a signalized interaction

Index was administered to measure the workload. Results showed that scores of each of the six subjective subscales (i.e., *mental demand, physical demand, temporal demand, overall performance, effort and frustration level*) of NASA TLX questionnaire were quite low. Moreover, many participants commented that the assistance provided by the driving aids outweighed its workload, and they found them helpful in assisting during various driving tasks.

Prior to the experimental drives, all the participants performed a practice (or warm-up) drive to become familiar with the simulator vehicle, driving environment, and all the driving messages that were transmitted during the experimental drives. Note that compliance with the information was left at the discretion of the participants. A number of strategies were implemented to account for possible learning effects. First, the driving scenarios were randomized. Two randomized driving conditions (i.e., baseline and perfect communication) were presented first, followed by another two randomized driving conditions (i.e., communication delay and loss). In this study, we intentionally did not place the communication delay and loss scenarios before the perfect communication drive to avoid any wrong perception about the connected environment by the participants. In the communication delay and communication loss scenarios, the time and location of these events were unknown to participants. Second, the driving environment, surrounding vehicles, and their colors were also changed across the drives. Third, in each drive, there were multiple events on the motorway and in the urban environment, and the participants were required to take a short break after each drive. Each participant took about 10 − 12 min 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 driving event from the previous drive(s).

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 informed about the designed driving route by showing a schematic diagram of the entire route (Fig. 1) consisting of motorway and Brisbane CBD. The motorway was connected to the city via an exit ramp, which was guided by road signs on the motorway. To guide the participants for driving in the city, all the possible turning movements at intersections were closed by placing cones except the desired route. 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. The participants were given a brief about the general theme of a particular drive (e.g., perfect communication, communication delay, and communication loss). After each drive, the participants were required to complete a NASA Task Load Index survey (Hart and Staveland, 1988). In addition, the participants were asked to complete the motion sickness assessment questionnaire adapted from Brooks et al. (2010). If any participant showed signs of motion sickness, s/he was not allowed to drive further in the experiment, and the corresponding data were excluded. Furthermore, at the end of the experiment, the participants filled out a post-driving survey, including questions on user acceptance, trust in the technology, and sensation-seeking behavior.

3.4. Driving behavior indicators

A variety of driving behavior indicators was analyzed for examining the impact of the connected environment. Table 3 presents the list of indicators investigated across various driving aids provided in the connected environment. A range of statistical analysis techniques was applied to compare and analyze the impact of various driving aids on different driving behaviors. A linear mixed model was used to test the significance of overall variation in a parameter where more than two scenarios were observed. Paired *t*-tests were applied for pairwise comparisons of a parameter between two scenarios. Fisher's exact test, which does not impose any restriction on the minimum number of frequencies in a cell, was conducted to examine the statistical association between two categorical variables. A 5% significance level was assumed for these statistical analyses.

4. Results

To analyze the driving performance across four drives, 78, 78, 74, and 73 trajectories were respectively obtained and evaluated for the baseline, perfect communication, communication delay, and communication loss driving conditions. Four and five participants were respectively unable to complete the driving in the communication delay and communication loss conditions due to motion sickness, thus forming an imbalanced dataset. Note that due to the imbalanced nature of data, a linear mixed model was utilized to examine the difference within and across the 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 4 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 spacing, average time headway, and time-to-collision (TTC). Note that the low-speed car-following only occurred in baseline and perfect communication (Table 1) driving conditions. During the low-speed car-following, the mean spacings 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 spacing 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 section, i.e., the lead vehicle was traveling at 85 km/h on 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 2). The mean spacings 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 spacing 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 ($p = 0.39$). However, the difference in spacing values between baseline and communication loss scenarios was statistically significant ($p < 0.001$). Similarly, the difference between perfect communication and communication loss scenarios was statistically significant ($p < 0.001$).

Meanwhile, the mean time headways along the high-speed car-following section 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 ($p = 0.615$). Although the differences were not statistically significant, the mean time headway was slightly longer in the communication loss scenario. This result suggests that drivers may compensate for the perceived risk of losing the driving assistance by increasing the time headway during high-speed car-following.

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 ($p < 0.001$), 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 speed limit exceedance was analyzed across road sections 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 5). The corresponding frequencies in the connected environment (perfect communication) scenarios were respectively 1373, 4, and 384. Fisher's exact tests revealed 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 5 (two-lane two-way highway: $p < 0.001$; four-lane two-way motorway: $p < 0.001$; and city environment: $p = < 0.001$).

Fig. 6 shows speed warnings per participant across various driving

Table 4
Effects of continuous driving aids on car-following behavior.

Car-following section	Car-following elements	Mean (SD)			Significance
		Baseline	PC	CL	*p*-value
Low-speed	Average spacing (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 spacing (m)	115.76 (56.41)	111.98 (49.52)	42.91 (1.61)	Paired *t*-test $_{B\ vs\ PC}$: 0.39; Paired *t*-test $_{B\ vs\ CL}$: < 0.001; Paired *t*-test $_{PC\ vs\ CL}$: < 0.001
	Average time headway (s)	7.75 (3.28)	8.24 (3.13)	8.56 (1.52)	Paired *t*-test $_{B\ vs\ PC}$: 0.092; Paired *t*-test $_{B\ vs\ CL}$: 0.601; Paired *t*-test $_{PC\ vs\ CL}$: 0.615;
	Minimum TTC (s)	3.55 (2.44)	7.33 (4.87)	4.73 (2.41)	Paired *t*-test $_{B\ vs\ PC}$: < 0.001; Paired *t*-test $_{B\ vs\ CL}$: < 0.001; Paired *t*-test $_{PC\ vs\ CL}$: < 0.001

PC: perfect communication; CL: communication loss; B: baseline.

Table 5
Impact of the 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	Fisher's exact 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	< 0.001

conditions. For the two-lane two-way highway, about 74 drivers in the baseline condition received more than five speed warnings throughout the drive, whereas 75 participants in the perfect communication scenarios received less than five speed warnings. A similar trend was observed for the four-lane two-way motorway and city environment. These results indicate that the connected environment helps drivers adapting their driving 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. Fisher's exact test indicated that tailgating frequencies between the baseline and perfect communication scenarios were not statistically different ($p = 0.621$).

4.2.2. Lane-changing driving aids

Mandatory and discretionary lane-changing interactions were programmed for the four-lane two-way motorway where drivers in the former were required to leave the current driving lane to reach a specific destination while in the latter, drivers changed lanes to gain speed advantage because the current driving lane was congested. The connected environment provided the information of the subsequent gaps available in the adjacent lane to decrease the workload and minimize judgment errors during the lane-changing decision-making. 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 6 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 crash 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 -5.25 m/s^2, respectively (Table 6). 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 6. 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 (measured by paired *t*-tests). Along with mean DRACs, the maximum DRAC across different driving scenarios during a mandatory lane-changing event was obtained and presented in Table 6. The maximum DRAC in the baseline condition was -7.09 m/s^2, but the maximum DRAC in the perfect communication scenario was -4.5 m/s^2. This result indicates that the connected environment offers a safer environment, which requires a lower DRAC to avoid safety-critical events during mandatory lane-changing maneuvers.

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/s^2, -3.35 m/s^2, -3.95 m/s^2, and -4.31 m/s^2. The differences in DRACs were found to

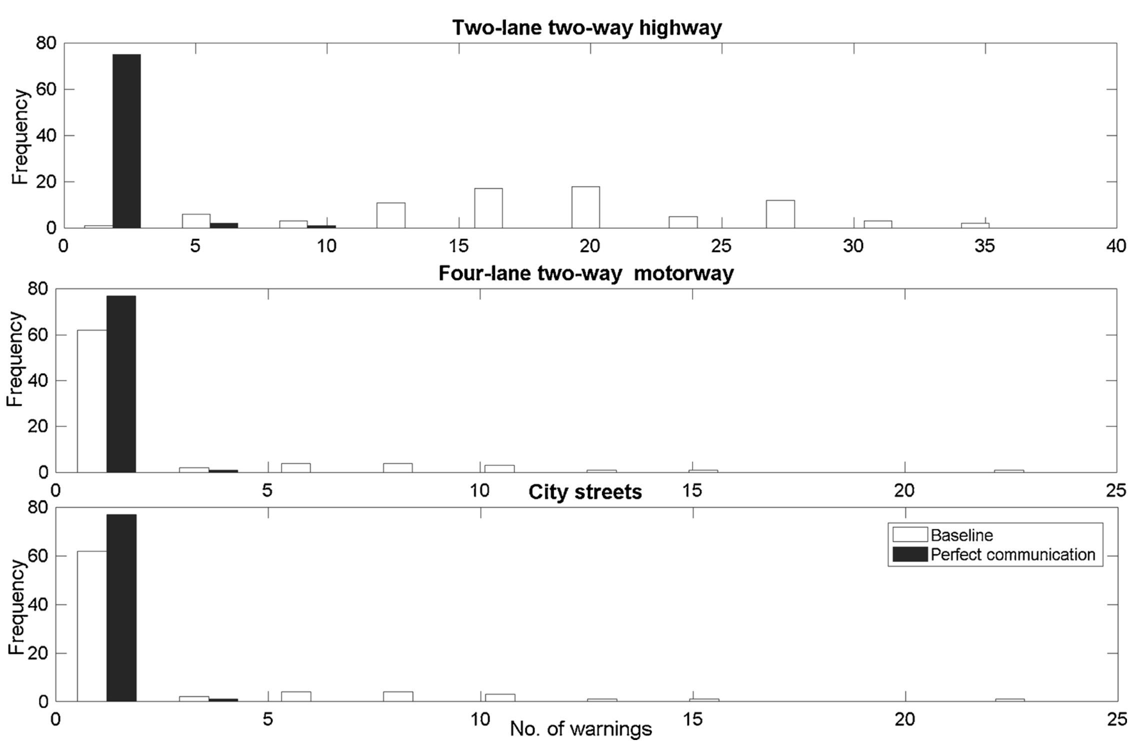

Fig. 6. Speed limit exceedance warnings per participant across three driving conditions.

Table 6
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/s^2	−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
Max DRAC, m/s^2	−7.09	−6.40	−4.5	−3.95	−5.11	−4.81	–	−5.27	–	–
Frequency of drivers exceeding -3.35 m/s^2	20	17	6	5	12	10	–	15	Fisher's exact test: < 0.001	Fisher's exact test: < 0.001

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

be statistically different across four drives as measured by the linear mixed model. Paired *t*-tests further revealed that the DRAC 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/s^2, 1.16 m/s^2, and 0.8 m/s^2, respectively, lower than that of the baseline condition, implying that the connected environment provided a higher safety margin during the discretionary lane-changing event. Similarly, the maximum DRAC values were lower for the connected environment conditions than the baseline condition.

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/s^2. 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/s^2 in the baseline, perfect communication, and communication delay scenarios (Table 6). This difference between these frequencies was found to be statistically different, as indicated by the Fisher's exact test ($p < 0.001$). Table 6 also shows that during discretionary lane-changing, 17 participants in the baseline condition required a DRAC higher than -3.35 m/s^2 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 Fisher's exact test, were found to be statistically significant ($p < 0.001$). These results suggest that the connected environment improves safety during lane-changing maneuvers as drivers in the connected environment are found to be less engaged in traffic conflicts (as 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 gain 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 the presence of a pedestrian on the zebra crossings. From the traffic light change scenario (refer to Fig. 5(c)), the frequency of running the yellow light was calculated. As reported in Table 7, the frequency of running the yellow light in the baseline condition was about twice that of the perfect communication scenario; the Fisher's exact test showed that the frequencies were statistically different ($p < 0.001$). Although the overall results indicate 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, there were still 27 (out of 78) participants who ran the yellow light in the connected environment. This finding reflect s that some drivers may have ignored the driving aids provided by the connected environment, or some risk-taking drivers may have exploited this information to estimate the time required to cross the intersection and ran the yellow light.

For the pedestrian scenario (Fig. 5(c)), time-to-collision (TTC) to the pedestrian was calculated when a driver interacted with the pedestrian entered a zebra crossing from the sidewalk. As reported in Table 7, the TTCs for the baseline and perfect communication scenarios were respectively 4.7 s and 4.9 s. A paired *t*-test showed that the 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 during 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 driving aids.

The findings of this study suggest that drivers adapt their driving behavior towards safer driving behavior when they are assisted with driving aids in the connected environment. Drivers were found to comply with driving aids, taking their maximum advantage to minimize decision errors, and thereby improve their driving behaviors. More discussion on the effects of the connected environment in various driving tasks is provided in ensuing paragraphs.

During the car-following scenarios, drivers in the connected environment were found to maintain larger spacings and longer time headways compared to driving in the baseline condition, implying that drivers have utilized the driving aids of the connected environment to improve safety. 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

Table 7
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 intersections	51	27	Fisher's exact 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

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 spacings 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 larger spacing 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 spacing along the low-speed section was around 30 m, whereas the average spacing along the high-speed section was around 112 m. It is obvious that drivers maintained higher spacings during high-speed car-following, and one of the possible reasons behind such large spacing values is that drivers were lagged behind the leader since they were unable to accelerate at a rate similar to that of the leader's acceleration rate. Another possible reason for large spacing values is that drivers need more space and time to react to any situation and control their vehicle safely at high-speeds (Loulizi et al., 2019). Given these large spacings during high-speed car-following, no statistical difference in spacings 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. As the connected environment provided the exact information on the distance from the leader car, drivers may have continuously maintained a higher margin from the lead vehicle to minimize the risk of rear-end collisions.

Drivers were found to adjust their speed selection behavior when they received speed limit exceedance warning in the connected environment. The frequency of speed limit exceedance warnings was found to be consistently lower in the connected environment compared to the baseline condition. Some of the past studies also reported that drivers complied 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 this driving simulator experiment, drivers continuously received real-time information on the spacing from the lead vehicle in the current lane. Drivers appear to exploit this information to drive more closely rather than to increase the distance from the lead vehicle. This finding opens an interesting question of whether this driving aid serves the purpose for which it is designed, or drivers utilize it in a counterproductive manner. This requires further investigation and is left for future research. In this study, tailgating warning aids were provided immediately after the critical event. 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 a certain time interval? This design choice may have significant implications on the effectiveness of the connected environment. These questions need to 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. In a traditional environment, drivers mainly rely on their experiences and consider the immediate gap in the target lane, which may be risky due to the uncertainty associated with estimating gap sizes and the speeds of the following vehicles. The connected environment, on the other hand, assisted drivers with subsequent gap information for minimizing decision errors and selecting a safer gap and thereby increasing safety margin. Microsimulation 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. In the baseline scenario, a large number of drivers ran the yellow light since they were in a dilemma whether to run the yellow light or wait. This inaccurate decision of yellow light running may increase the crash risk significantly. Drivers in the connected environment with the information on traffic light changing, on the other hand, were found to run the yellow light less often. Bar-Gera et al. (2013) reported that a driver assistance system with audio and visual information about stopping at a signal reduced the red-light running violation by 96 %. Moreover, Yan et al. (2014) evaluated the effectiveness of an in-vehicle system on red-light running events at signalized intersections and found that the collision rate is lower when driving with the system compared to that of without the system.

Drivers in the real driving conditions are often found to detect pedestrians very close to zebra crossings, and as a result, they take evasive actions like hard decelerations, which could lead to rear-end collisions with following vehicles. In this study, it has been found that the advisory driving aid for the pedestrian's presence on a zebra crossing is 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, which 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 warnings at intersections and found a very positive response about the usefulness of pedestrian safety warnings. In addition, Yue et al. (2018) proposed a combined framework for driving assistance with the connected vehicle technology and reported that the framework has the capability to reduce crashes between light vehicles and pedestrians.

Driving behavior (i.e., measured by the indicators listed in Table 3) was also analyzed across three age groups: young drivers (18–26 years; 32 participants), middle-aged drivers (27–50 years; 38 participants), and older drivers (> 50 years; 8 participants), and across driver's gender. During the car-following scenario (both low-speed and high-speed), middle-aged and older drivers maintained larger average spacings, longer time headways, and longer TTCs compared to young drivers in all driving conditions. In the literature, young drivers, who are generally inexperienced and risk-takers, are reported to drive very close to the leader and have shorter TTCs (Leung and Starmer, 2005; Montgomery et al., 2014; Ali et al., 2019), which is consistent with the findings of this study. In the connected environment, the car-following behavior of young drivers is found to be less risky as they have longer TTCs, revealing a significant change towards safer driving behavior by young drivers. Similarly, female drivers were found to maintain larger spacings, longer time headways, and longer TTCs compared to male drivers in all car-following conditions. It is intuitive as male drivers are generally reported to be associated with risky driving compared to female drivers (Iversen and Rundmo, 2004; Montgomery et al., 2014). Interestingly, the driving behavior of male drivers has been found to be improved towards safer driving in the connected environment, as they found to maintain longer TTCs and larger spacings in the connected environment. Similar results were observed for lane-changing (both mandatory and discretionary) events, interactions with a pedestrian, and interactions with a traffic light.

The findings of this study are expected to improve our understanding of how drivers make decisions in different driving tasks when a connected environment assists them. The findings of this study could be particularly useful for designing vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications that can assist drivers in dangerous situations. These findings will also guide vehicle manufacturers in designing safety features for automated vehicles. For instance, speed exceedance warnings can avoid the negative impacts of speeding. Similarly, providing gap information in a lane-changing scenario can assist drivers in selecting an appropriate gap in the target lane and reduce crash risk. Furthermore, vehicle manufacturers can utilize the design of driving aids presented in this study for their driving assistance systems, and wherever needed, they can improve the existing design to present the information effectively.

The connected environment is expected to provide information via V2V and V2I communications using sensors and LIDARS (Kim, 2015). In a real-world setting, it is anticipated that information transfer may not work all the time perfectly 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 (measured in terms of TTCs and spacings) has been improved significantly, but it deteriorates when driving aids are delayed by 1.5 s. However, compared to the baseline condition, safety margins are still better when driving aids are delayed because driving aids are still available, although with a delay, to assist during driving tasks. Notably, the effects of communication loss were even worse compared to no driving aids (i.e., baseline condition), as drivers may try to extract information from the connected environment when it was not available due to the communication loss. Since the impairments in the connected environment only occurred during two driving tasks on the motorway, the findings above cannot be generalized to other road traffic environments. An in-depth investigation is needed on how the communication loss influences driving behavior during traffic interactions in an urban environment.

6. Conclusions

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. Various driving behavior indicators for each of these scenarios have been compared between the baseline and connected environment conditions.

Drivers in the connected environment were found to maintain a higher safety margin as they have been found to maintain a larger spacing and a longer time headway during car-following. 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. During the lane-changing decision-making process in the traditional environment, drivers only estimate the immediate gap in the adjacent lane visible by the naked eye. This study has found that when drivers receive the lane-changing gap information in the connected environment, they tend to perform both mandatory and discretionary lane-changing maneuvers with a higher safety margin as measured by the deceleration required to avoid the crash (DRAC).

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 the presence of a pedestrian 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. This study has found that 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 running a yellow light 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, it should be noted that the benefits of the connected environment are the maximum when the communication is perfect. Any impairment in the connected environment, such as communication delay and communication loss, is likely to deteriorate safety compared to the perfect communication scenario. Although this study delayed the driving aids in communication delay scenario by 1.5 s based on a pilot study and previous research (Talebpour et al., 2016), more research is required to understand the impact of delayed driving aids on driving behavior. Such work is left for future research.

This study investigated the effects of communication impairments such as communication delay and communication loss only on particular driving events along the highway. A worthwhile research direction would be investigating the effects of communication impairments across other traffic interactions. Furthermore, driving aids were disseminated on the windscreen similar to a heads-up display; however, the latest vehicle technologies are using a big screen (similar to iPad) to share information with drivers. Thus, it is worth investigating to study 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.

While this study is conducted in a high-fidelity driving simulator, the realism of driving and the level of perceived risk may not be the same as real-world driving. As such, field testing of the connected environment should be conducted for similar driving tasks as employed in this study to validate the findings further and develop more insights into the impact of the connected environment on driving behavior and safety in real-world driving conditions. Furthermore, in this study, drivers were exposed to the connected environment for a short period. A worthwhile research direction would be examining driving behavior when drivers are exposed to a connected environment for a long time. In particular, driving behavioral adaptation and reliance on the connected environment technologies should be thoroughly investigated. The pre-driving survey (i.e., driving behavior information) and post-driving survey (i.e., user acceptance, trust in the technology, and sensation-seeking) data collected in this experiment have not been analyzed as they are beyond the scope of this paper. An interesting research direction would be examining the relationship between self-reported behavior and driving performances in the connected environment.

CRediT authorship contribution statement

Yasir Ali: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing - original draft, Visualization. **Anshuman Sharma:** Conceptualization, Methodology, Software, Data curation, Writing - review & editing. **Md. Mazharul Haque:** Conceptualization, Methodology, Investigation, Validation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Zuduo Zheng:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Mohammad Saifuzzaman:** Methodology, Data curation, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2020.105643.

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