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Cooperate or not? Exploring drivers' interactions and response times to a lane-changing request in a connected environment

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ABSTRACT: Lane-changing is one of the complex driving tasks that depends on the number of vehicles, objectives, and lanes. A driver often needs to respond to a lane-changing request of a lane-changer, which is a function of their personality traits and the current driving conditions. A connected environment is expected to assist during the lane-changing decision-making process by increasing situational awareness of surrounding traffic through vehicle-to-vehicle communication and vehicle-to-infrastructure communication. Although lane changing decision making process in a traditional environment (an environment without driving aids) has been frequently investigated, our understanding of drivers' interactions during the lane-changing decision-making process in a connected environment remains elusive due to the novelty of the connected environment and the scarcity of relevant data. As such, this study examines drivers' responses to lane-changing requests in a connected environment using the CARRS-Q Advanced Driving Simulator. Seventy-eight participants responded to the lane-changing request of a lane-changer under two randomised driving conditions: baseline (traditional environment without driving aids) and connected environment (with driving aids). A segmentation-based approach is employed to extract drivers' responses to the lane-changing request and subsequently estimate their response time from trajectory data. Additionally, drivers' response times are modelled using a random parameter accelerated failure time (AFT) hazard-based duration model. Results reveal that drivers tend to be more cooperative in response to a lane-changing request in the connected environment compared with the baseline condition whereby they tend to accelerate to avoid the lane-changing request. The AFT model suggests that on average drivers' response times are shorter in the connected environment, implying that drivers respond to the lane-changing request faster in the presence of driving aids. However, at the individual level, connected environment's impact on drivers' response times is mixed as drivers' response times may increase or decrease in the connected environment compared to the baseline condition, for instance, we find that female drivers have lower response times in the connected environment than that of male drivers. Overall, this study finds that drivers in connected environment, on average, take less time to respond and appear to be more cooperative, and thus, are less likely to be engaged in safety-critical events.

KEY WORDS: ***lane-changing; response time; connected environment; driving simulator; random parameter; duration model.***

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1. Introduction

A connected environment disseminates information related to surrounding traffic by means of vehicle-to-vehicle communication and vehicle-to-infrastructure communication. Such information will fundamentally transform how humans travel, and can assist in mitigating massive transport related issues such as road crashes, efficiency, and emissions. One possible application of a connected environment is to minimise perception and judgement errors during lane-changing, which may result in a crash. For instance, in 2017, 1,171 crashes were associated with lane-changing in New South Wales, Australia (TfNSW, 2019), while lane-changing crashes account for 4% of the total crashes in Queensland, Australia (DTMR, 2018). Apart from negative impact on traffic safety, lane-changing also causes disruption to traffic flow such as stop-and-go oscillations (Ahn and Cassidy, 2007, Zheng et al., 2011) and capacity drop (Cassidy and Rudjanakanoknad, 2005), etc. Thus, analysing and modelling lane-changing behaviour remain an area of interest for researchers in the past decade or so.

Lane-changing is a complex driving task that depends on surrounding traffic dynamics, number of lanes, and objectives. A typical lane-changing decision-making process involves a subject vehicle (i.e., lane-changer), its leader, and its follower on the current driving lane as well as on the target lane. During a typical decision-making process, at least two players are often involved: a lane-changer who makes lane-changing request/action and a responder who responds to a lane-changing request/action (i.e., immediate follower of the lane-changer on the target lane). Factors that govern drivers' lane-changing decisions (mandatory or discretionary) and execution of lane-changing are well-known and thoroughly studied in the literature (Ahmed et al., 1996, Toledo and Zohar, 2007, Li et al., 2015b). In contrast, lane-changing is often considered as a one-way decision-making process (Zheng, 2014), i.e., the lane-changer is the only one who makes the decision; however, the immediate follower, who is often required to respond to the lane-changing request, is generally ignored. Such ignorance could lead to a lane-changing collision and unrealistic estimates of a lane-changing model (Ali et al., 2019b). How the immediate follower responds to the lane-changing request of the lane changer, and how much time the follower takes to respond to the lane-changing request are some of the questions that remain unanswered, and thus motivates the present study.

Response time is one of the common parameters used for understanding longitudinal driving behaviour (i.e., car following) when drivers are exposed to different driving conditions. For instance, response (or reaction) time has been frequently used in the past research to investigate: (a) the impact of distraction (especially mobile phone) on driving behaviour (Hancock et al., 2003, Törnros and Bolling, 2006, Caird et al., 2008, Just et al., 2008, Ishigami and Klein, 2009, Haque and Washington, 2014); (b) drivers' responses to advanced warning messages provided by a connected environment (Sharma et al., 2019); (c) intersection design with dynamic use of exit-lanes for left-turn (Zhao et al., 2015); (d) auditory alerts for in-vehicle information systems (Wiese and Lee, 2004), etc. Furthermore, it has been linked to traffic flow efficiency (Kesting and Treiber, 2008, Hoogendoorn et al., 2014) and traffic safety (Dingus et al., 2006). Despite its huge importance and compared to long history of response time studies in car-following context, comparatively the response time has been rarely studied in the lane-changing context. Moreover, inconsistencies in defining the response time are found (more detail in Section 2.1) in the existing studies. Thus, this study focusses on the response time during the lane-changing decision-making process.

A connected environment informs drivers about the surrounding traffic information, such as the speed of and the distance to the lead vehicle. Such information can not only reduce the propensity of making decision/judgement errors that may lead to lane-changing collisions, but also assist in making more informed and efficient lane-changing decisions. In general, when the lane-changer signals for a lane-change, the follower on the target lane of the lane-changer often makes a decision in response to the lane-changing attempt (often modelled as a game in the literature (Ali et al., 2019b, Talebpour et al., 2015, Liu et al., 2007). The follower's decision is a function of their personality traits and surrounding traffic conditions. An aggressive driver, for instance, is likely to ignore the lane-changing attempt while a cooperative driver is expected to show courtesy and give way to the lane-changer. Similarly, when the inserting gap is large (too small), the follower may (not) show courtesy. In addition, how the follower's decision (e.g., aggressive or cooperative) changes when they receive driving aids provided by a connected environment needs to be explored. Along this line, several studies in the past have hypothesised that when drivers are aware of other drivers' intentions (by means of driving aids), drivers are expected to be more cooperative (Amoozadeh et al., 2015, Guériau et al., 2016). However, no concrete evidence exists to verify such hypothesis primarily because of the scarcity of data in a connected environment. Moreover, driving behaviour varies greatly across different age groups and gender, and it is very likely that driving aids influence each driver differently. A good understanding of a connected environment's differential impact on age and gender will help in improving the design and thereby the effectiveness of driving aids.

The objective of this study, therefore, is to understand drivers' responses to the lane-changing request in a connected environment with driving aids. To this end, the rest of the paper is structured as follows: Section 2 reviews studies related to response time, drivers' responses to lane-changing, and response time in a connected environment. Section 3 describes the experimental methodology and data collection including the scenario design, driving behaviour indicators, and the statistical modelling approach. Section 4 presents descriptive and model estimation results. Section 5 discusses the effects of the connected environment on driver's response times. Finally, Section 6 concludes the study with possible future research directions.

2. Literature review

This section is divided into three subsections: (a) studies related to response time; (b) drivers' responses to lane-changing; and (c) response time in a connected environment.

2.1. A review of studies related to response time

Response time, one of the fundamental driving performance indicators that explains driving behaviour, has been widely used for measuring drivers' responses/reactions when they are exposed to different conditions such as distraction, collision warnings, advanced driving assistance systems, to mention a few. Table 1 summarises representative studies in the literature related to response time. Notably, most of these studies have focussed on response time in a car-following scenario while response time in a lane-changing event has been rarely studied.

Various definitions of the response time during lane-changing exist in the literature. Lee and Kwon (2001), for instance, defined response time as the time required to complete a lane-changing manoeuvre. Ye et al. (2008) defined response time as time needed for manoeuvring including drivers' reaction times. In another study, response time is called reaction time and defined as the time duration required to complete a lane-changing manoeuvre (Li et al., 2015a). Similarly, Li et al. (2015b) defined the response time as drivers' reactions to traffic signs and the time required to complete a lane-changing manoeuvre. Hayat et al. (2016) defined response time as the combination of perception–reaction time and a lane-changing manoeuvring time. Beck et al. (2017) defined response time as the time difference between recognising the obstacle and the start of a lane-changing manoeuvre.

Table 1. A summary of studies related to response time

Study	*Objective*	*Driving behaviour*	*Response times (s)*	*Modelling technique*
Lee et al. (2002)	Distracted drivers' response to collision warning	Car-following	0.76 – 1.73	Descriptive
Lamble et al. (2002)	Impaired drivers' responses to brake light	Car-following	0.57 – 0.76	Descriptive
Consiglio et al. (2003)	Drivers' response to secondary tasks	Car-following	0.39 – 0.46	Descriptive
Wiese and Lee (2004)	Driver response to auditory in-vehicle systems	Car-following	0.3 – 1	Descriptive
Goh and Wong (2004)	Drivers' response to change in a traffic signal	Interaction to a traffic signal	0.4 – 5.2	Linear regression
Rimini-Doering et al. (2005)	Drowsy drivers' response to lane departure warning	Lateral movement	0.4	Descriptive
Santos et al. (2005)	Drivers' response to in-vehicle information system on the standardised secondary visual search task	Lateral movement	1.6 – 4.5	Descriptive
Abe and Richardson (2006)	Drivers' response to alarm timing on collision warning systems	Car-following	0.86 – 1.04	Descriptive
Bustamante et al. (2007)	Drivers' response to varying alarm system and increased workload	Car-following	3.62 – 5.2	Receiver operating characteristic curves
Porter et al. (2008)	Drivers' response to auditory safety alerts	Car-following	1.9 – 3.2	Descriptive
Bellinger et al. (2009)	Drivers; response to use of cellular phone and listening to music	Car-following	0.39 – 0.64	Descriptive
Al-Darrab et al. (2009)	Driver response time when distracted by mobile phone	Car-following	0.2 – 0.9	Descriptive
(Wang et al., 2010)	Driver response to different in-vehicle informational interfaces	Car-following	4 – 7	Descriptive
Bella and Russo (2011)	Drivers' response to a collision warning system	Car-following	1.35	Linear regression
Nowakowski et al. (2012)	Driver response to real-time end-of-queue alerting system	Car-following	NA	Descriptive
Liu and Jhuang (2012)	Drivers' response to in-vehicle warning information	Car-following	1.4 – 1.66	Descriptive
Dozza (2013)	Analysing factors affecting response time for evasive manoeuvres	Car-following	0.1 – 4.7	Descriptive
Haque and Washington (2015)	Drivers' responses to pedestrian crossing in distracted conditions	Car-following	2.4 – 3.4	Survival model
Li et al. (2014)	Drivers' response to flashing brake and hazard systems in avoiding rear-end crashes	Car-following	1.52 – 2.23	Descriptive
Li et al. (2015b)	Drivers' response to smart advisory system	Lane-changing	17.5 – 34.4	Descriptive
Li et al. (2015a)	Impact of socio-demographics on driver response	Lane-changing	8 – 32	Fuzzy-logic model
Ruscio et al. (2015)	Driver braking response to collision warning	Car-following	0.1 – 0.56	Descriptive
You et al. (2016)	Drivers' response to a left turn warning in a work zone area	Turning manoeuvring	2.5	Descriptive
Beck et al. (2017)	Drivers' response to in-vehicle side view displays layouts in critical lane-changing situation	Lane-changing	1.03 – 1.38	Descriptive
Jurecki and Stańczyk (2018)	Drivers' response to pedestrian in crash situations	Interaction to pedestrian	0.6 – 2	Linear regression
Sharma et al. (2019)	Drivers' response to advanced warning messages	Car-following	1.56 – 2.43	Descriptive
Atwood et al. (2019)	Active warning system in level-2 automated vehicle	Car-following	2.7	Negative binomial regression

The aforementioned studies suggest that lane-changing response time is sometimes either confused with lane-changing execution (or duration) or considered as the summation of the reaction time and lane-changing duration. However, in the literature, lane-changing duration is defined as the time taken by a lane-changer to complete its lane-changing manoeuvre from the initial lane to the target lane, which is intuitive (Toledo and Zohar, 2007, Moridpour et al., 2010, Cao et al., 2016, Ali et al., 2018). As Sharma et al. (2019) highlighted inconsistencies in defining the response time in the car-following context and provided a proper definition of the response time as "*the time taken by a driver to adjust his/her speed against a stimulus, with or without deliberately delaying his/her decision*". Similarly, there is a need to clearly define response time in a lane-changing context.

The synthesis of existing literature reveals that most of the studies have focussed on lane-changing response time in a traditional environment (i.e., an environment where drivers do not receive surrounding traffic information) while in a connected environment, where drivers are aware of surrounding traffic dynamics and expected to be cooperative, responses to a lane-changing manoeuvre are still unexplored. Such information would not only help in identifying aggressive groups of drivers and suggest remedial measures for them, but can also assist in developing more realistic lane-changing models.

2.2. Drivers' responses to lane-changing

A few studies have described drivers' responses to a lane-changing manoeuvre. For instance, Zheng et al. (2013) found that a follower undergoes three stages during a lane-changing manoeuvre: (a) anticipation (the change in driving behaviour of the follower when s/he notices the lane-changing request), (b) relaxation (where the follower and its leader are willing to accept a shorter spacing and then relax to normal spacing), and (c) change in the follower's behaviour (an aggressive (timid) driver becomes less aggressive (timid)). Similar observations have been reported by other researchers (Ghaffari et al., 2015, Li et al., 2018). These studies only consider the case where the follower is assumed to yield (or show courtesy) to a successful lane-changing manoeuvre, however, past research suggests that followers may try to avoid a lane-changing request by accelerating and closing down the lag gap (Hidas, 2002, Talebpour et al., 2015, Kang and Rakha, 2017, Ali et al., 2019b). Hence, more research is required to understand and characterise the follower's behaviour (or response) to the lane-changing request, also in the context of a connected environment in order to verify hypotheses that drivers would make more efficient and safer decisions in such an environment.

2.3. Response time in a connected environment

A connected environment allows exchange of traffic information with roadside units and/or other vehicles, which can warn drivers about hazardous situations within or out of sights and thereby reduce crash risk. For instance, Wan et al. (2016) analysed the effects of lead time of verbal collision warning messages on car-following behaviour and reported that gradual braking and shorter response time of drivers when the lead time was between 5 to 8 s. Chrysler et al. (2015) concluded that drivers identified potential threat sooner in a connected environment compared to a traditional environment, resulting in shorter response times. Lin et al. (2016) reported longer response times of drivers in a connected environment in hazardous conditions such as fog, which contrasts the findings of several past studies. In a recent driving simulator study, Wu et al. (2018) found shorter response times in a connected environment in reduced visibility driving conditions (e.g., fog) compared to driving without warning system. A study on drivers' response times to freeway merge advisories in a connected environment found an inverse relationship of response time with available merging gaps. This study concluded that drivers have shorter response times when they receive advisory message in a connected environment compared to when driving without it (Hayat et al., 2016).

A survey of the literature suggests that most of the studies related to response time in a connected environment are in car-following context while not much research is conducted for lane-changing. This is mainly because car-following has received a significant attention in the literature while lane-changing itself has not received due attention to date, and response time is one important component of lane-changing, which needs to be further investigated.

Much of the existing research for lane-changing in a connected environment is either hypothesised or tested by numerical simulations. Although numerical simulation is a reasonable compromise to the scarcity of data in a connected environment, human factors, which are critical in lane-changing decision-making (Sharma et al., 2018), are often ignored. Furthermore, impacts or benefits of connectivity at a microscopic level have been reported in previous research (Ali et al., 2020, Ali et al., 2019a, Ali et al., 2018), especially for the lane-changer, while impacts and benefits for the immediate follower are yet to be explored.

3. Experimental methodology and data collection

This section explains vehicular interactions, design of the connected environment, various driving performance indicators selected for this study, and statistical model formulation.

3.1. Experiment design

Due to the novelty of a connected environment and scarcity of the relevant data, an innovative driving simulator experiment was designed and employed in this study. As data related to lane-changing, such as when the indicator starts for signalling lane-changing intentions and failed lane-changing attempts, can be risky and difficult to obtain from real trajectory data, the Centre for Accident Research and Road Safety-Queensland (CARRS-Q) Advanced Driving Simulator is utilised that provides a controlled driving environment and flexibility of collecting the data without safety concerns. Participants were asked to drive on a motorway in two randomised driving conditions: baseline driving (without driving aids; same as the traditional driving environment) and connected environment (with driving aids). The baseline driving condition is considered the ‘default’ driving condition to which the driving performance is compared. The connected environment driving condition enables the comparison of driving when drivers received surrounding traffic information required for the lane-changing decision-making.

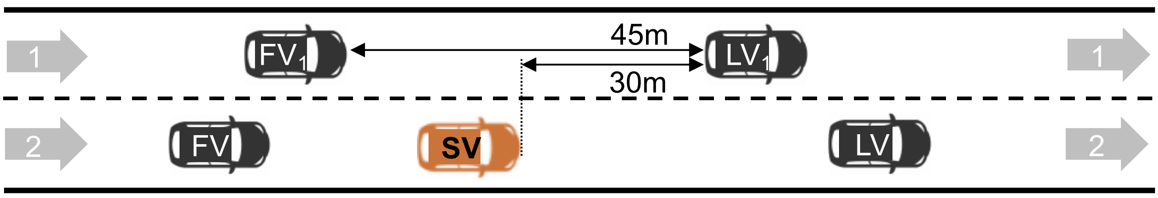
3.1.1. Advanced Driving Simulator

To collect high quality vehicle trajectory data in the connected environment, the CARRS-Q Advanced Driving Simulator was utilised (Figure 1a). The driving simulator consists of a Holden Commodore car with fully functioning controls. There were three projectors in front of the simulator car, providing a high resolution 180° field of view. The simulator car is attached to a rotating base capable of providing six degrees-of-freedom, mimicking real driving features like acceleration, deceleration, braking, cornering, and road surface. The simulator car is controlled by SCANeR™ studio software that connects eight computers for controlling the simulator car dynamics and virtual environment. To enhance realism of driving, the simulator car produces simulated engine noises, vehicle-road interaction noises, and noises of other traffic interactions. The SCANeR™ software automatically records basic driving related variables such as speeds, accelerations and positions at a frequency of 20 Hz.

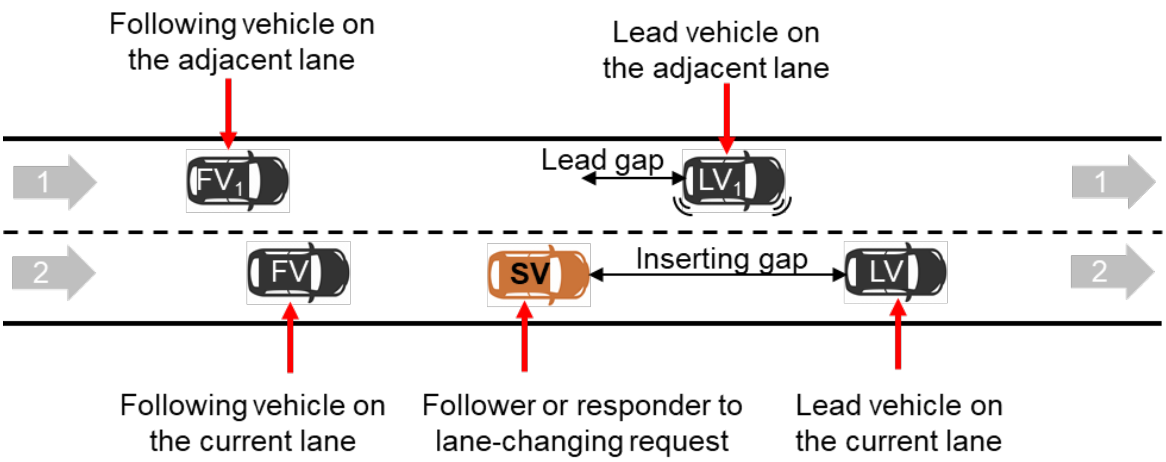
3.1.2. Participants

By advertising at various public places and social media platforms, 78 participants with a diverse background were recruited for this study. The mean age of the participants was 30.8 years (standard deviation [SD] 11.70 years), and 64% were male. The average driving experience of the participants was 12.2 (SD 11.5) years. About 20% of the participants held a provisional driving licence while about 10% of the participants were involved in a traffic crash in the past one year. Approximately 62% of the participants possessed a university degree. Each of the participant was paid AUD 75 as a compensation of their time.

(a) The CARRS-Q Advanced Driving Simulator



(b) Vehicular interactions at the start of lane-changing scenario



(c) Lead vehicle starts signalling for lane-changing to SV's lane

Fig. 1. The Advanced Driving Simulator and design of vehicular interactions (not to scale) in the experiment

3.1.3. Design of vehicular interactions

A hypothetical 3.2 km long four-lane motorway with two lanes in each direction was designed. The posted speed limit on the motorway was 100 km/h. The motorway was designed in accordance to Australian road standards where cars drive on the left. The designed motorway consisted of various mandatory lane-changing and discretionary lane-changing events and failed lane-changing attempts, however, this paper is limited to analysing drivers' responses when a programmed vehicle signalled for lane-changing. To avoid learning effects, driving conditions were randomised for each participant.

Baseline driving condition: In this scenario, each participant drove the simulator vehicle without driving aids. At the start of scenario, there was a subject vehicle (SV, driven by the participants), as well as several computer-controlled vehicles, namely the lead vehicle (LV) and the following vehicle (FV) on the current lane 2 while FV_1 and LV_1 were travelling on adjacent lane 1. The clear gap between these vehicles was 45 m and the lead gap (i.e., the distance between the rear bumper of LV_1 on lane 1 and the front bumper of SV on lane 2) was 30 m (see Figure 1b for illustration). After travelling about 200 m from the start, LV_1 was scripted to start indicating (or signalling) for lane-changing to lane 2 where SV was travelling (Figure 1c) and SV was asked to respond to the lane-changing request of LV_1.

In order to provide identical vehicular interactions and ensure that all the participants receive the lane-changing request at the same location, we scripted the programmed vehicles to drive at the same speed as SV.

Connected environment driving condition: During this scenario, the vehicular interactions remained the same as in the case of the baseline condition, however, participants were assisted with driving aids, mimicking vehicle-to-vehicle communication and vehicle-to-infrastructure communication. For the design of driving aids, a thorough literature review was conducted, and also designs of major car manufacturers were reviewed to determine how information is disseminated to drivers. By utilising this knowledge, the driving aids in the simulator experiment were provided into two forms: imagery (a text message) and auditory (a beep sound).

Four driving aids were provided in the connected driving environment condition, namely fixed messages, advisory messages, warning messages, and lane-changing gap messages. Fixed messages were continuously available on the left side of the windscreen, describing the speed of and the distance to the leader on the current lane (Figure 2(a)). These messages assisted drivers in responding to the lane-changing request. Advisory messages were presented in the text form along with a beep sound at the bottom centre of the windscreen. These messages informed the participants about the upcoming situations such as the current lane is closed (Figure 2(a)). Warning messages popped up on the left side of the windscreen along with beep sound, warning about critical situations such as over-speeding (Figure 2(a)) and tailgating. The lane-changing gap information appeared on the left side of the windscreen with a beep sound whenever a lane-changing opportunity is available (Figure 2(b)).

3.2. Data and analysis

3.2.1. Dataset

Seventy-eight participants drove in two driving conditions (i.e., baseline and connected environment), and a total of 156 trajectories from 78 participants were obtained and used for analysis. A wide range of variables were collected by the simulator such as speeds, accelerations, positions, spacings, and lateral profiles. In addition to trajectory data, driver demographics were collected using a pre-driving questionnaire survey that included age, gender, licence type, driving experience, self-reported crash history, and educational background.

(a) Warning message (speed violations), fixed messages (speed of and distance to head vehicle), advisory message (text message about upcoming situations)

(b) Lane-changing information regarding gaps on the adjacent lane

Fig. 2. Design of the driving aids in the connected environment.

3.2.2. Driving performance indicators

In this study, different driving performance indicators are utilised for measuring drivers' responses to the lane-changing request. Table 2 provides a list of variables selected for this study. As mentioned in Section 2, there is no clear consensus on defining the response time, this study, therefore, defines the response time as the time taken by the subject vehicle (i.e., follower in this case) to respond to a stimulus (i.e., the lane-changing request generated by turning signalling or indicator of the lead vehicle from the adjacent lane). This definition is consistent with Sharma et al. (2019) who also reported inconsistencies in defining the response time during a car-following scenario and defined the response time in car-following context.

Table 2. Driving performance indicator selected for this study

Parameter	*Definition*
Response time	The time taken by the subject vehicle to respond to the lane-changing request of the lead vehicle on the adjacent lane
Inserting gap	The distance from the rear bumper of the lead vehicle to the front bumper of the subject vehicle on the current lane
Lead gap	The (longitudinal) distance between the rear bumper of the lead vehicle on the adjacent lane to the front bumper of the subject vehicle on the current lane

3.2.3. Data processing

Response time is a physical measure consisting of drivers' sensation, perception, and decision (Sharma et al., 2019). It is difficult to obtain the response time directly from trajectory data sources, hence a sound methodology is required to extract response time. As such, this study adopts a segmentation-based approach to estimate the response time and drivers' responses to the lane-changing request. More specifically, the Bottom-Up algorithm (Keogh and Pazzani, 1998) performs a linear piecewise approximation of speed profiles of drivers. The Bottom-Up algorithm has been successfully tested in past research to segment traffic data (Zheng et al., 2011). We then adopted the definition of Ozaki (1993), which states that a driver's response can be classified as in a steady-state condition if the slope is within 0.05*g* (where *g* is the acceleration due to gravity). Following the approach of Ali et al. (2019b), if the slope is positive (negative) and higher (lower) than 0.05*g*, it is termed an acceleration (deceleration) state. A typical example of the original and segmented speed profiles can be seen in Figure 3.

The response time t_{iq} for each driver $i \in \{1, \ldots, 78\}$ and driving condition $q \in \{1, 2\}$ (baseline and connected environment), is calculated as the time difference between the start of the lead vehicle indicator (Point A in Figure 3) and the first point where the first segment starts (either acceleration or deceleration obtained from the Bottom-Up algorithm; Point B in Figure 3). The response time measured using the aforementioned method is compared to the response time calculated using accelerator and brake pedal movements in the simulator. More specifically, the response time is the summation of two time periods as shown in Equation 1,

$$t_{iq} = t_{\text{ar}} + t_{\text{bp}}, \tag{1}$$

where t_{ar} is the time difference between when the lead vehicle starts signalling and the subject vehicle releases the accelerator pedal, and t_{bp} is the time difference between when the accelerator pedal and brake pedals are released and pressed, respectively. For instance, t_{ar} and t_{bp} obtained from simulator data for vehicle ID 61 during the baseline condition are respectively 2 s and 1.8 s, resulting in a response time of 3.8 s. Results obtained from accelerator and brake pedal movements confirm the accuracy of the method presented in this study to obtain the response time.

3.2.4. Hazard-based duration model

Hazard-based duration (or survival) models are the best suited for modelling duration data. More specifically, these models are adopted when a need arises to model elapsed time until an event occurs (Haque and Washington, 2015). Duration models are frequently used to model the reaction time of distracted drivers (Haque and Washington, 2014), braking behaviour when approaching pedestrian crossings (Bella and Silvestri, 2016), minimum gap time during a lane-changing collision (Ali et al., 2019a), and possibility of lane-changing collision (Ali et al., 2020). In this study, a duration model is developed for the response time (duration or dependent) variable—the length of the time between the start of indicator by the lead vehicle (i.e., lane-changer) on the adjacent lane and the time when the subject vehicle (follower) responds to the lane-changing request. The developed model is a function of operational variables (e.g., initial speed and inserting gap), driving condition (i.e., baseline and connected environment), and driver demographics. A summary of descriptive statistics of the independent variables is presented in Table 3.

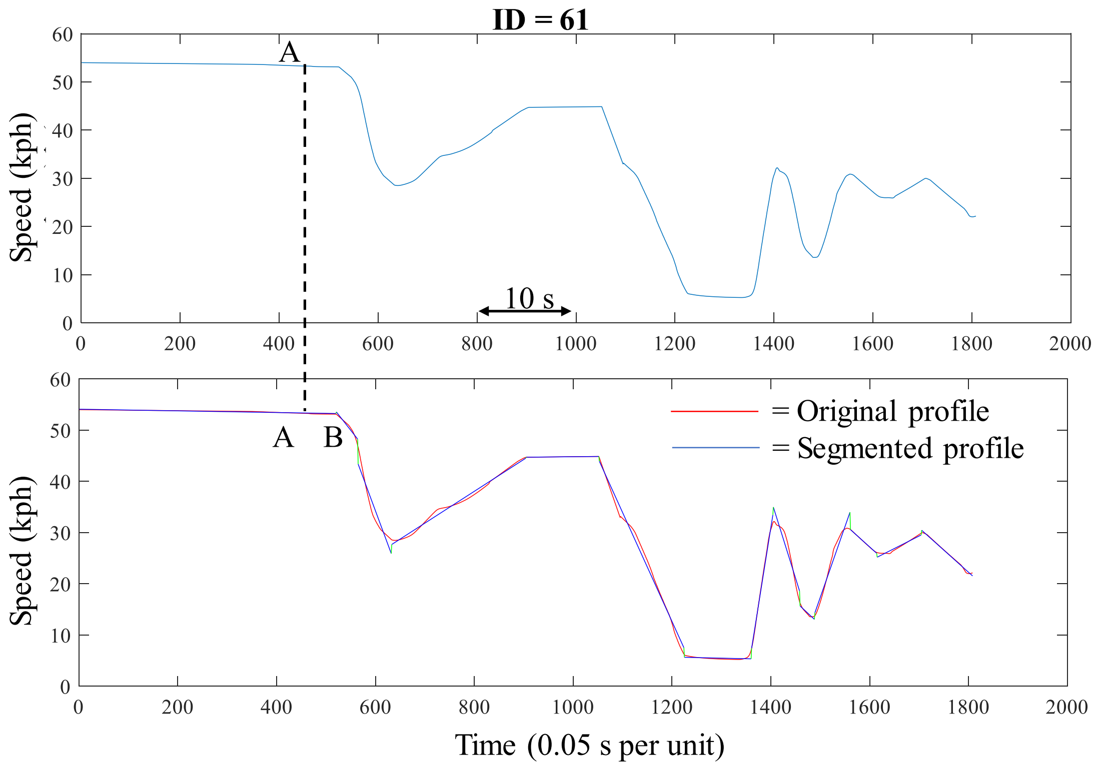


Fig. 3. An example of original and segmented speed profiles; *A = LV starts indicating for lane-changing; B = SV responds to the lane-changing request of the lead vehicle obtained from the segmentation-based approach*

Table 3. Descriptive statistics of explanatory variables considered for duration models

Variable	*Description of variables*	*Count*	*Percentage*	*Mean (SD)*
Driving condition				
Baseline	Driving without driving aids (reference)	78	100	—
Connected environment	Driving with driving aids (dummy)	78	100	—
Operational variables				
Initial speed	Instantaneous speed (kph)	—	—	66.4 (12.3)
Inserting gap	Front gap to the lead vehicle (m)	—	—	23.1 (11.1)
Demographic variables				
Age groups				
Young	Participant is 18 – 26 years old (dummy)	38	48.72	—
Middle-aged	Participant is 27 – 50 years old (reference)	32	41.03	—
Older	Participant is 51+ years old (dummy)	8	10.26	—
Gender				
Male	Participant is male (reference)	50	64.10	—
Female	Participant is female (dummy)	28	35.90	—

The duration variable (i.e., response time) is a continuous random variable T with a cumulative density function $F(t)$ and probability density function $f(t)$. In the case of the response time, $F(t)$ provides the probability of a driver responding to the lane-changing request before some specified time *t*. The survival function, $S(t)$, gives the probability of the duration variable being greater than some specified time *t* as shown in Equation (2).

$$F(t) = \Pr(T \leq t) = 1 - \Pr(T > t) = 1 - S(t). \tag{2}$$

Traditionally, two parametric approaches are used to incorporate the effects of covariates on the survival function, namely proportional hazard and accelerated failure time (AFT). The former approach assumes hazard ratios as constant over time and factors that affect the duration variables act in a multiplicative fashion on some underlying hazard function. In contrast, the latter approach allows the covariates to rescale (accelerate) time directly compared to a baseline survivor function where all covariates are zero (Washington et al., 2011). The functional formulation for AFT can be written as

$$S(t) = S_0\left(t\exp(\boldsymbol{\beta}'\mathbf{X}_{iq})\right), \tag{3}$$

where S_0 is the underlying survivor function, $\boldsymbol{\beta}$ indicates a (column) vector of unknown and to be estimated parameters, and $\mathbf{X}_{iq}$ denotes a (column) vector of explanatory variables as defined in Table 3. Since $\mathbf{X}_{iq}$ includes driver demographics, our model allows heterogeneity in response time across drivers of different gender and age groups. In addition, AFT assumes an intrinsically linear function of the logarithm of the response (survival) time that varies linearly with explanatory variables as shown in Equation (4).

$$\ln(t_{iq}) = \boldsymbol{\beta}'\mathbf{X}_{iq} + \varepsilon_{iq}. \tag{4}$$

In this study, a parametric survival model is assumed, and it is required to specify a distribution of ε for estimating Equation (3). In the literature (Haque and Washington, 2015, Haque and Washington, 2014, Washington et al., 2011), a wide range of distributions are available including lognormal, exponential, Weibull, log-logistic, etc. In this study, we assume that all error terms are independently and identically distributed (IID), $\varepsilon_{iq} \sim N(0,\sigma^2)$, such that response time t_{iq} follows a lognormal distribution with mean $\mu_{iq} = \boldsymbol{\beta}'\mathbf{X}_{iq}$ and standard deviation σ. The lognormal distribution exhibits non-monotonic hazard rates (initially increasing and then decreasing). An Anderson-Darling test confirms that a lognormal distribution fits well with the response time data (A^2= 0.51; *p*-value = 0.65). The selection of a lognormal distribution is also consistent with the reported literature (Koppa, 2000, Rakha et al., 2007). The parametric survivor and density functions for the lognormal distribution are provided in Equations (5) and (6), respectively:

$$S(t) = 1 - \Phi\left(\frac{\ln(t) - \mu_{iq}}{\sigma}\right), \tag{5}$$

$$f(t) = \frac{1}{t\sigma\sqrt{2\pi}}\exp\left(-\frac{1}{2\sigma^2}\left(\ln(t) - \mu_{iq}\right)^2\right), \tag{6}$$

where $\Phi(\cdot)$ denotes the standard normal cumulative distribution function.

Instead of only assuming fixed parameters and main effects, we also estimated models with one or more random parameters (with various distributions), one or more interaction effects. We adopted a maximum likelihood approach using quasi-Monte Carlo simulation with 1000 Halton draws (see e.g., Bhat (2003)) in which we account for the panel nature of the data (i.e., each participant drives both in the baseline and connected environment). Based on model fit (via the Akaike Information Criterion), model estimation convergence, and the interpretability and level of statistical significance of the parameter estimates, we decided to include a normally distributed random parameter for the connected environment dummy while keeping all other parameters fixed, and to include an interaction effect between gender and driving conditions. Including random effects for the connected environment also allows us to analyse the variation in change of driving behaviour compared to the baseline condition. This model setting is also known as *group random parameters* (Oviedo-Trespalacios et al., 2020, Eker et al., 2019, Fountas et al., 2018, Heydari et al., 2018), implying that the parameters follow a certain probability distribution across the observation with each group (or repeated drive).

We also tried a random constant to include random heterogeneity in driving behaviour across both driving conditions, and we tried various nonlinear transformations of the variables, but these models do not perform well.

3.2.5. Classification and decision tree

As mentioned above, random effects in the model reveals different driving behaviour, which needs to be understood and properly classified. To this end, this study employs a classification approach.

Classification, one of the frequently adopted machine learning approaches, is used for classifying data into the number of classes. Mainly, there are two types of approaches: supervised learning and unsupervised learning. The former approach learns from the training data and then classifies new data according to learnings from training data. Whereas the latter approach uncovers the underlying information present in the data, which is mainly unlabelled (Kotsiantis et al., 2007, Chaovalit and Zhou, 2005). This study adopts a supervised learning approach for classifying drivers' response times.

A wide range of classification learning algorithms are available in the literature. This study adopts six different classification algorithms, namely decision tree, discriminant analysis, support vector machine (SVM), *k*-nearest neighbour, ensembles, and neural network. As these algorithms are widely used in the machine learning domain and the focus of this study is not on developing any new algorithm, these algorithms are not described here and we refer interested readers to Kotsiantis et al. (2007) for a comprehensive and excellent review of these algorithms. To test the efficacy of these algorithms, two criteria, as reported by Kotsiantis et al. (2007), are selected: (a) accuracy; and (b) classification interpretability. The accuracy of the selected algorithms is calculated using *k*-fold cross-validation where $k = 4$ in this study. The accuracy is determined as

$$\text{validation} = 100 \times \left(1 - \frac{1}{k}\sum_{j=1}^{k} MSE_j\right), \tag{7}$$

where MSE_j represents the mean squared error of the j^{th} cross-validation dataset between the observed class and the predicted class of drivers in the j^{th} dataset.

Based on the higher accuracy and classification interpretability, a machine learning algorithm is selected (i.e., decision tree) and used for classification (more discussion to follow in Section 4.1.4). Before applying the decision tree, we can also determine the importance (or ranking) of features (or explanatory variables) considered in this study. This helps in identifying the significant parameters (both driving performance and driver characteristics) that influence drivers' response times in a connected environment. To this end, ReliefF algorithm is used (Urbanowicz et al., 2018) to rank different features.

4. Results

This section explains drivers' responses to the lane-changing request, descriptive analysis, and model estimation results.

4.1. Drivers' responses to the lane-changing request

4.1.1. Descriptive analysis of drivers' responses

As mentioned earlier that it is unknown how drivers respond to the lane-changing request of the lane-changer, a frequency analysis of drivers' responses is carried out. To classify the drivers' responses into different classes, the same segmentation-based approach is adopted as discussed in Section 3.2.3. More specifically, three classes of responses are obtained from the data, namely accelerating to ignore the lane-changing request (slope is greater than 0.05*g*), decelerating to show courtesy to the lane-changer's request (slope is lower than -0.05*g*), or doing nothing in response to the lane-changing request of lane-changer (slope between 0.05*g* and -0.05*g*). Table 4 presents the frequencies (and percentages) of drivers' responses that are obtained from this segmentation-based approach. Respectively, 12.82% and 2.56% of followers tend to accelerate to ignore the lane-changing request of the lane-changer in the baseline and connected environment driving conditions, and this difference is significant at a 95% confidence level. Similarly, 46.15% and 62.82% of followers show courtesy (cooperation) to the lane-changing request in the baseline and connected environment driving conditions, respectively. Again, the difference is statistically significant. Two noteworthy observations from this frequency analysis are: (a) aggressiveness of drivers is lowered in the connected environment; and (b) drivers become more cooperative in the connected environment. These findings coincide with Guériau et al. (2016) who reported cooperative behaviour under the connected driving environment, and with Ali et al. (2019b) who suggested that drivers in a connected environment tend to avoid risky manoeuvres.

To understand how much time followers take to respond to the lane-changing request (denoted by the turning indicator), a descriptive analysis is conducted. Response times for each participant in both the baseline and connected environment are shown in Figure 4 and aggregated results are presented in Table 5. The average response time in the baseline condition is 1.59 s (SD 1.53 s) while the corresponding average response time in the connected environment is 1.13 s (SD 1.06 s). A paired *t*-test indicates a statistically significant difference in response time between the connected environment and the baseline condition, implying that drivers on average respond faster to the lane-changing request of the lane-changer when they are assisted with driving aids, but as it is clear in Figure 4 there are also many cases where the response time increases in the connected environment. We conduct a more detailed analysis on factors that influence response times in the following subsections.

Table 4. Drivers' responses to the lane-changing request

Response	*Baseline*	*Connected env.*	*Significance*	*Remark*
Accelerating	10 (12.82%)	2 (2.56%)	$\chi^2 = 5.77$; p-value = 0.01	Significant
Decelerating	36 (46.15%)	49 (62.82%)	$\chi^2 = 4.36$; p-value = 0.03	Significant
Doing nothing	32 (41.03%)	27 (34.62%)	$\chi^2 = 0.68$; p-value = 0.41	Not significant

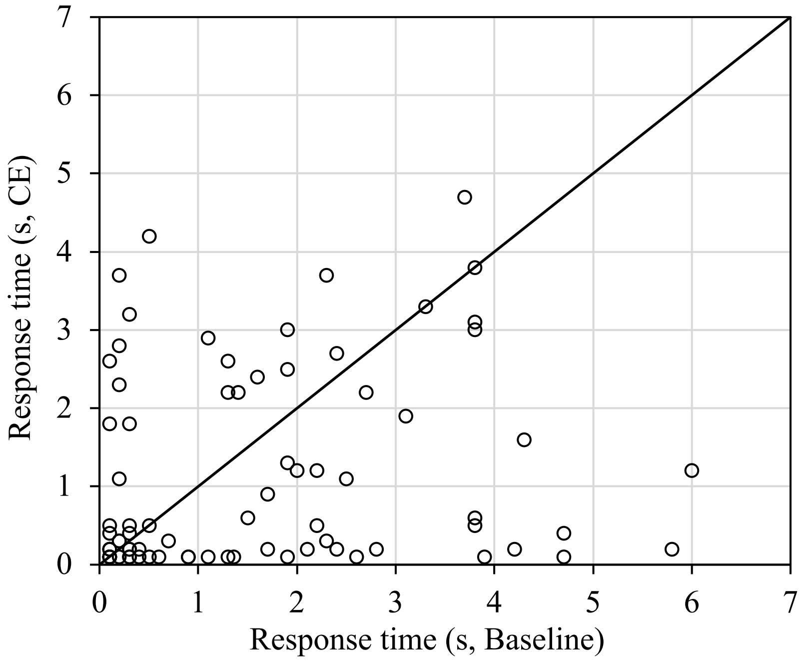


Fig. 4. Response times for baseline and connected environment (CE) driving conditions

Table 5. Descriptive analysis of the response time and associated parameters

Parameters	*Baseline (SD)*	*Connected env. (SD)*	*Significance*	*Remark*
Avg. response time (s)	1.59 (1.53)	1.13 (1.06)	$t = 2.03$; p-value = 0.043	Significant
Avg. inserting gap (m)	20.43 (8.17)	25.41 (7.80)	$t = 2.24$; p-value = 0.026	Significant
Avg. lead gap (m)	5.37 (4.22)	9.21 (3.92)	$t = 2.15$; p-value = 0.032	Significant

The average inserting gaps—the distance between the front bumper of the subject vehicle to the rear bumper of the lead vehicle on the current driving lane—for the baseline and connected environment driving conditions are respectively 20.43 m (SD 8.17 m) and 25.41 m (SD 7.80 m). The difference in average inserting gap between the connected environment and the baseline condition is again statistically significant. A larger inserting gap represents a higher safety margin.

The average lead gap—the distance between the rear bumper of the lead vehicle on the adjacent lane to the front bumper of the subject vehicle on the current lane—in the baseline condition is 5.37 m (SD 4.22 m) while the corresponding lead gap in the connected environment is 9.21 m (SD 3.92 m). The difference in average lead gap between the connected environment and the baseline condition is again statistically significant.

Table 6 shows the model estimation results for the random parameter AFT model fitted to the response time data. All parameter estimates are statistically significant at the 95% confidence level. As mentioned earlier, the baseline survivor function of the fitted model is specified by a lognormal distribution, and the parameter for the connected environment dummy is found to be random and normally distributed. In addition to the connected environment, the final parsimonious model contains non-random parameters for the initial speed, inserting gap, young and older drivers, and for an interaction effect between female driver and connected environment dummy variables. Mean response times (μ_{iq}) for lane changing can be computed using Equation (6), where S is a standard normally distributed variable.

Table 6. Model estimation results of random parameters AFT model of the response time

						95% CI	
Variable	*estimate*	*s.e.*	*z-value*	*p-value*	*exp(β)*	*lower*	*upper*
Constant	2.946	0.329	8.94	<0.001			
Initial speed	-0.048	0.004	-12.0	<0.001	0.953	-0.055	-0.040
Inserting gap	0.017	0.007	2.41	0.016	1.021	0.003	0.031
Young driver	-0.314	0.154	-2.03	0.042	0.731	-0.616	-0.012
Older driver	-0.525	0.210	-2.50	0.012	0.591	-0.937	-0.113
Connected env. (mean)	-0.399	0.191	-2.08	0.037	0.671	-0.773	-0.025
Connected env. (SD)	0.395	0.135	2.91	0.003			
Connected env. x Female	-0.103	0.050	-2.06	0.040	0.902	-0.201	-0.005
Error variance (σ)	0.865	0.060	13.18	<0.001			
LL = -202.97; AIC = 423; No. of observations = 156; No. of clusters = 78; Cluster size = 2							

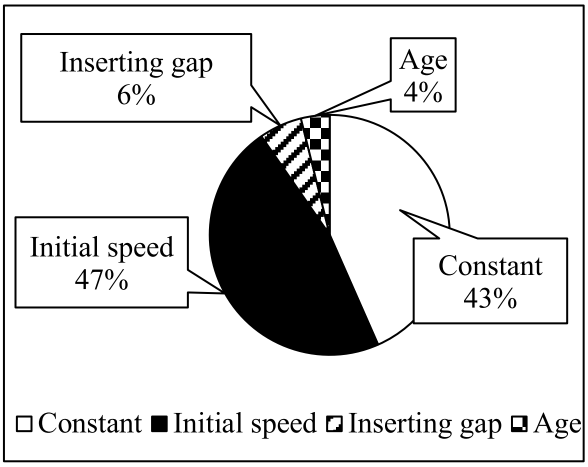
$$
\begin{aligned}
\text{mean response time} = \exp\big(& \ 2.946 \\
& -0.048 \times \text{InitialSpeed} \\
& +0.017 \times \text{InsertingGap} \\
& -0.314 \times \text{YoungDriver} \\
& -0.525 \times \text{OlderDriver} \\
& -0.399 \times \text{ConnectedEnvironment} \\
& +0.395 \times \text{ConnectedEnvironment} \times S \\
& -0.103 \times \text{ConnectedEnvironment} \times \text{Female}\big).
\end{aligned} \tag{6}
$$

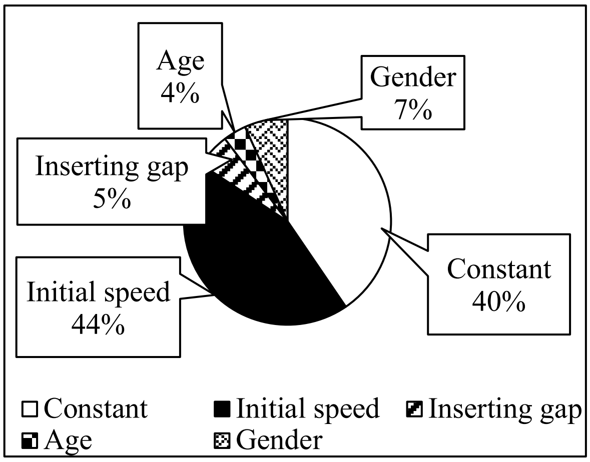
4.1.2. Response times in the baseline

To gain insights into parameter estimates, the exponent of each coefficient is shown in Table 6, reflecting the percentage change in the response time corresponding to a unit increase in the continuous variable and a change from zero to one for categorical variables (Washington et al., 2011, Haque and Washington, 2015). Initial speed is significant and found to be negatively associated with the response time. More specifically, one kph increase in the initial speed tends to decrease the response time by 4.7%. One possible reason could be that when the initial speed is higher, drivers tend to react faster to avoid collisions with the lead vehicle (i.e., lane-changer) (Brown et al., 2001).

Inserting gap has a significant and positive impact on the response time. The exponent of parameter estimates suggests that one metre increase in the inserting gap tends to increase the response time by 2.1%, which is intuitive because when drivers have larger inserting gaps available to them, they will have more flexibility in responding without any safety concern.

Young and older drivers are more likely to have shorter response times compared to middle-aged drivers. More specifically, the response times of young and older drivers are respectively 26.9% and 40.9% shorter than that of middle-aged drivers. While it is well-known that younger people generally have shorter response times (Bilban et al., 2009), it may be surprising to see a shorter response time for older drivers. We elaborate this finding in Section 5.1.1.





(a) (b)

Fig. 5. Relative importance of the explanatory variables in the model (a) Baseline; (b) Connected environment

Figure 5 displays the relative importance of the explanatory variables considered in the model that explains how much each explanatory variable contributes to the model. The relative importance is calculated as the ratio of the estimate of an explanatory variable (e.g., initial speed, inserting gap, etc.) to the utility range total (i.e., sum of estimates of all the explanatory variables). In contrast to relative importance computations based on the minimum and maximum partworths (excluding the constant) proposed in Orme (2010), we compute relative importance based on the average parthworths, which allows to also include the constant. Apart from the constant term, initial speed is the most influencing factor among other variables affecting response times of drivers in the baseline condition (Figure 5(a)).

4.1.3. Response times in the connected environment

Table 6 indicates that the mean impact of the connected environment on the response time is related to gender difference. Females have a 9.8% lower response time in a connected environment than men. The distribution of the random parameter for the connected environment dummy is depicted in Figure 6. Not only is its mean statistically significant, but also its standard deviation, indicating significant heterogeneity in response times in the connected environment where according to Figure 6 response times decrease for most drivers (88.7%), but not necessarily for all.

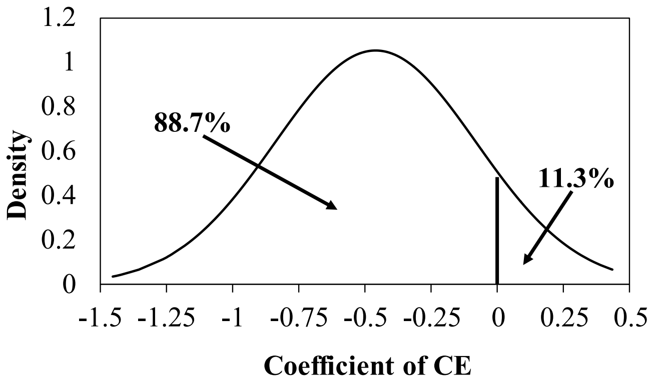


Fig. 6. Distribution of coefficients of the connected environment

Figure 5(b) indicates the relative importance of the independent variables for the connected environment driving condition in the model. Similar to the baseline condition, initial speed contributes the highest compared to other variables in the model.

Figure 7 displays the model prediction accuracy for both the driving conditions. For the connected environment, lower and upper bounds are also plotted. The Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are calculated for each driving condition using the developed model. The MAEs (RMSEs) for the baseline and connected environment are respectively 1.74 s (2.22 s) and 0.90 s (1.81 s). Overall, the estimated model shows a reasonable prediction accuracy for the response time in both the driving conditions.

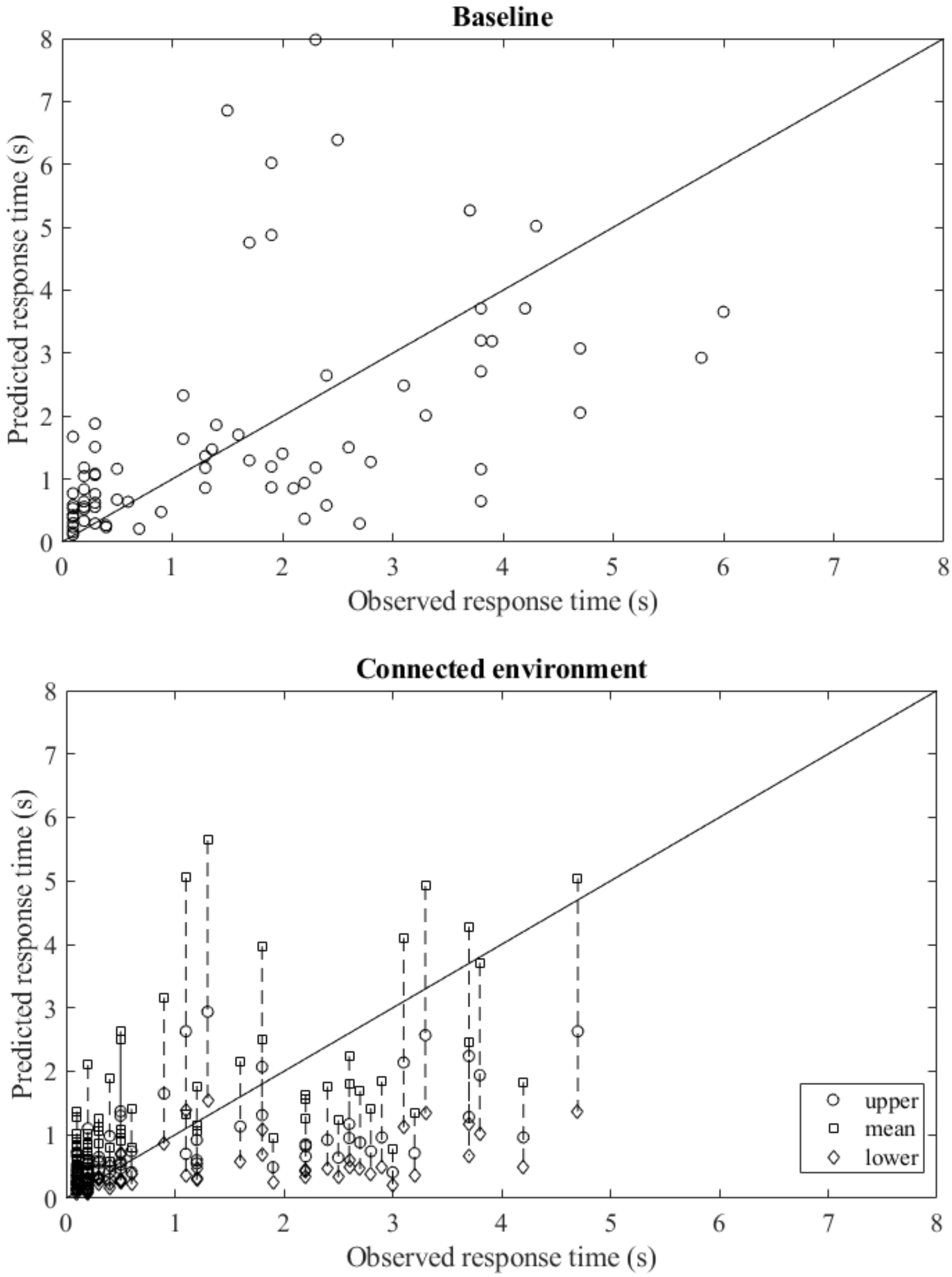


Fig. 7. Model prediction accuracy

4.1.4. Understanding the differential response time in the connected environment

As mentioned above, driver responses in the connected environment can be either way: an increased response time or a decreased response time compared to the baseline condition. Thus, there is a need to understand and identify the factors (both driving performance indicators and driver characteristics) that lead to differential response time behaviour in the connected environment. As such, this study first assesses various classification algorithms (described in Section 3.2.5), and then using the best algorithm, a set of factors are used to classify drivers' response times into two groups.

Table 7 presents the explanatory variables (called features in machine learning) used to classify increased or decreased response times of drivers in the connected environment. In total, seven features are considered to classify differential response time. The initial speed ratio, defined as the initial speed in the connected environment divided by the initial speed in the baseline environment, and inserting gap ratio, similarly defined as the ratio of the inserting gap in the connected and baseline environment, are used as features that indicate changes between driving conditions. Other features such as age, gender, education, driving experience, and licence types have been described previously.

Table 8 shows that the highest accuracy is achieved when five features are considered, namely inserting gap ratio, initial speed ratio, driving experience, licence type, and education. The algorithms with the highest accuracy are decision trees (fine tree), support vector machine (Quadratic SVM), ensemble (bagged tress and random forest), and neural networks (multilayer perceptron). However, decision trees provide the most straightforward interpretability as reported in Kotsiantis et al. (2007), and is thus selected in this study.

The ranking of features (in descending order) obtained from ReliefF algorithm (Urbanowicz et al., 2018) is inserting gap ratio, initial gap ratio, driving experience, licence type, and education (Figure 8). This ranking is consistent with the ranking of neural networks, decision tree, and ensemble algorithms. A relative comparative analysis of factors suggests that driving performance indicators (i.e., inserting gap ratio and initial speed ratio) have the highest influence on the increase or decrease of the response time in the connected environment. Moreover, the most important factor that will govern the increase or decrease of the response time in the connected environment is inserting gap ratio whereas the driving experience is the most important factor among all the human factors considered.

Table 7. A summary of features (or explanatory variables) used in the classification algorithms

Features	*Coding*
Initial speed ratio	1 = range (0 1]; 2 = range (1 2]; 3 = range (2 3]
Inserting gap ratio	1 = range (0 1]; 2 = range (1 2]; 3 = range (2 3]
Age group	1 = Young; 2 = Middle; 3 = Older
Gender	1 = Male; 2 = Female
Education	1 = Primary; 2 = Junior; 3 = Senior; 4 = TAFE; 5 = University
Years of driving experience	1 = (1 10]; 2 = (10 20]; 3 = (20 30]; 4 = (30 40]; 5 = (40 50]
Licence type	1 = Open; 2 = Provisional
Response variable	A = Increased response time in CE; B = Decreased response time in CE

CE: Connected environment

Table 8. Comparison of classification algorithms considered in this study

Classifier	Subclass	Validation accuracy with all features (%)	Highest validation accuracy with 6 features (%)	Highest validation accuracy with 5 features (%)	Highest Validation accuracy with 4 features (%)
Decision Trees (Classification tree)	Fine Tree	75.6	75.6	77.6	75.6
	Medium Tree	75.6	75.6	75.6	75.6
	Coarse Tree	75.6	75.6	76.9	76.9
Discriminant Analysis	Linear Discriminant	61.5	67.9	62.8	60.3
	Quadratic Discriminant	65.5	66.7	67.9	67.9
Support vector machines (SVM)	Linear SVM	67.9	69.2	70.5	74.4
	Quadratic SVM	59	62.8	71.8	74.4
	Cubic SVM	61.5	70.5	66.7	76.9
	Fine Gaussian SVM	65.4	66.7	65.4	70.5
	Medium Gaussian SVM	65.4	65.4	66.7	70.5
	Coarse Gaussian SVM	64.1	64.1	64.1	61.5
k-Nearest Neighbour (KNN)	Fine KNN	67.9	66.7	64.1	64.1
	Medium KNN	56.4	69.2	65.4	70.5
	Coarse KNN	64.1	64.1	64.1	56.4
	Cosine KNN	65.4	69.2	66.7	64.1
	Cubic KNN	52.6	65.4	64.1	55.1
	Weighted KNN	66.7	67.9	64.1	71.8
Ensembles	Boosted Trees	64.1	64.1	64.1	64.3
	Bagged Trees	75.6	75.6	74.1	73.1
	Random forest	65.3	84	76	80.6
Neural Network	Multilayer perceptron	69.4	78	73	76.9

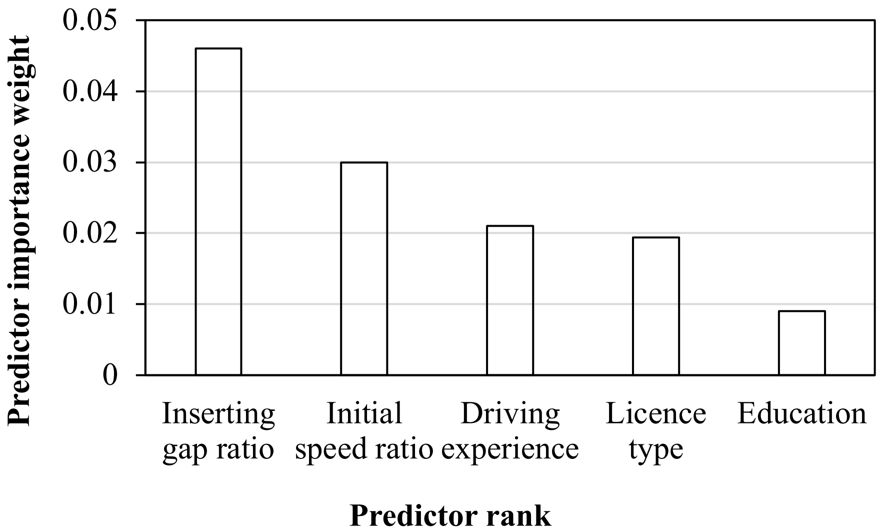


Fig. 8. Ranking of features based on ReliefF algorithm

Figure 9 presents the classification decision tree. Considering the right branch of the tree, it can be observed that in the connected environment, if the initial speed is higher than that of the baseline condition and the driving experience is high, then it is more likely that the response time will decrease (i.e., *B*). This is consistent with our findings reported in the previous section. Note that driving experience can be considered as a surrogate to driver age. Moreover, when initial speed is higher in the connected environment and driving experience is lower and licence type is provisional, response time is more likely to decrease in the connected environment. Similarly, the rest of the right branch of the tree can be interpreted.

Considering the left branch of the tree (Figure 9), when both the initial speed and the inserting gap are lower in the connected environment compared to the baseline condition, then response time is more likely to decrease in the connected environment. Moving further down, for drivers whose driving experience is lower and inserting gap is higher in the connected environment compared to the baseline condition, the response time increases in the connected environment.

Two noteworthy conclusions from the decision tree are: (a) for the majority of drivers, response time decreases while there exists a significant heterogeneity in the response time when drivers receive driving aids from the connected environment (complements our modelling results); and (b) a necessary condition for increase in response time is that inserting gap in the connected environment is greater than inserting gap in the baseline condition. This finding is intuitive, because if drivers have enough gap in front of them there is no need to respond quickly.

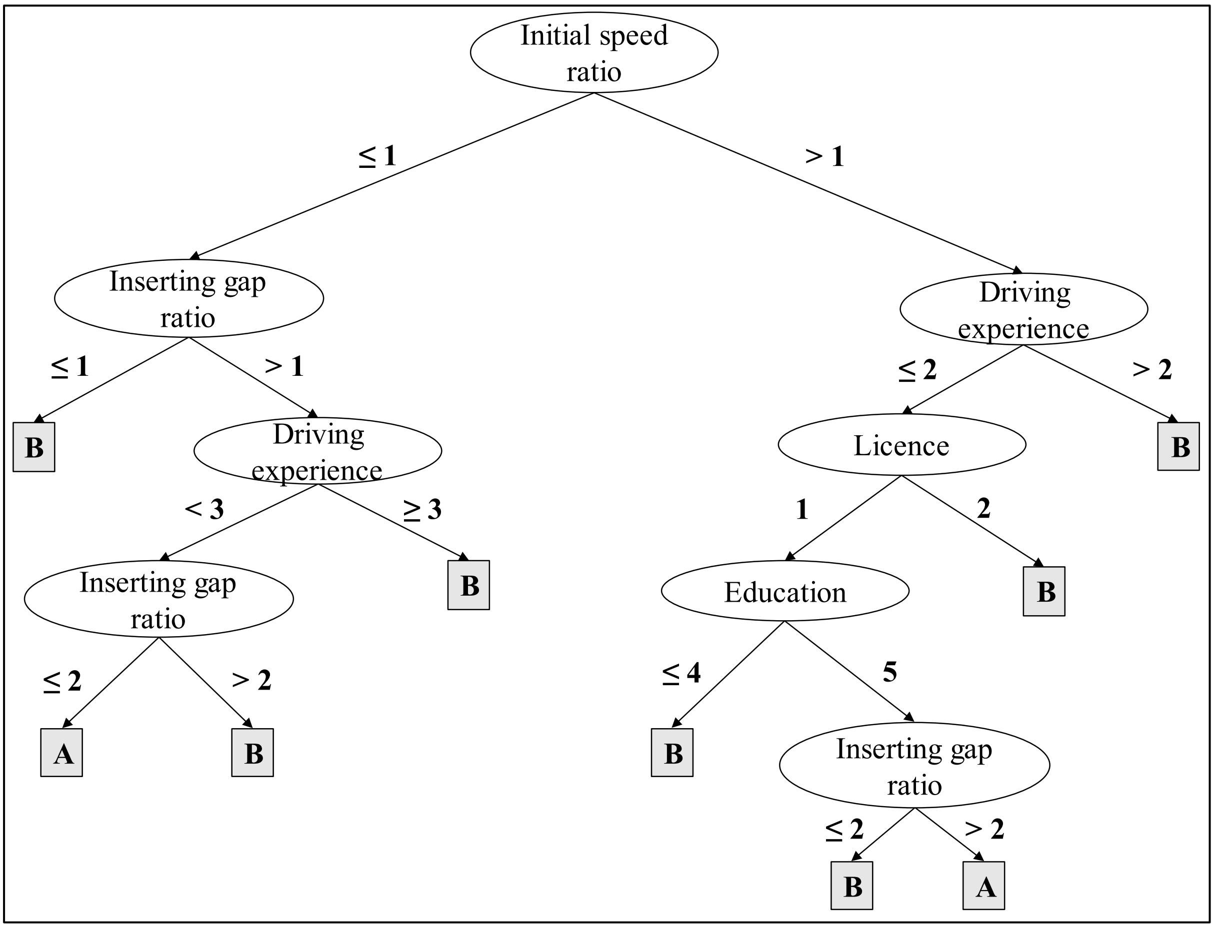


Fig. 9. Fine decision tree for classifying increased/decreased response time in the connected environment; *A & B respectively denote increased and decreased response times*

5. Discussion

5.1. Drivers' responses in the connected environment

The developed random parameter AFT model for the response time provides insights into how a driver's response time varies over time and how different driver characteristics and driving conditions (connected environment or not) affect this response time. Using the survival function presented in Equation (5) and the parameter estimates reported in Table 6, we compute survival probabilities of not responding to the lane-changing request, see Figure 10. More specifically, the survival probabilities after a response time of 1 s are respectively 72%, 37%, 67%, and 15% for the baseline condition, mean connected environment (i.e., mean of the connected environment's coefficient), connected environment with the lower limit (i.e. mean - 1.645 × standard deviation), and connected environment with the upper limit (i.e., mean + 1.645 × standard deviation). The corresponding probabilities at a response time of 2 s are 42%, 13%, 25%, and 3%, respectively. This indicates that the probability of not responding to the lane-changing request decreases over the time. Moreover, drivers in the connected environment respond on average 2.1 times faster to the lane-changing request. In addition, drivers in the connected environment not only exhibit proactive behaviour, but also show a cooperative behaviour when they were assisted with driving aids. The shorter response times of drivers in the connected environment could be: (i) an indicator of a higher cooperation between drivers during the lane-changing decision-making process; and (ii) an indicator that drivers are not willing to engage in safety critical events because a delayed response is likely to require an evasive action (e.g., hard braking), which is consistent with Chang et al. (2009) who reported shorter response times of drivers when they received in-vehicle information compared to that of drivers without in-vehicle information. Guériau et al. (2016) reported a similar cooperative behaviour during lane-changing interactions in the connected environment using numerical simulations. In the connected environment, drivers are aware about intentions of other drivers, and with such information, drivers become more cooperative and increase overall safety during the lane-changing interactions. This finding agrees well with our previous finding (reported in Table 4) that about 63% of drivers show courtesy to the lane-changer in the connected environment while only 2% of drivers tend to ignore the lane-changing request by accelerating (i.e., aggressive behaviour). By contrast, drivers are more aggressive in the baseline condition (without the presence of the information) as 13% of drivers accelerated to ignore the lane-changing request, about 5 times higher than in the connected environment.

From the survival curves shown in Figure 10, it is observed that drivers tend to respond faster in the connected environment. Hayat et al. (2016) reported that drivers' perception-reaction times decrease when they receive advisory information from the connected vehicle environment. Similarly, Yun et al. (2015) found that drivers in the connected environment respond quickly during a car-following scenario compared to driving without the connected environment. A possible reason for early response of drivers in the connected environment could be situational and surrounding traffic awareness, which leads drivers to respond to the lane-changing request quickly. Similar findings have been reported in other research (Liu and Jhuang, 2012, Ho et al., 2006) where shorter response times of drivers are observed when they are exposed to different situations in the presence of in-vehicle information.

On the other hand, a driver's response time may also increase in a connected environment. Sharma et al. (2019), for example, reported that the connected environment increases response time during a hard-braking event in a car-following scenario. The authors argued that the awareness of surrounding traffic conditions and advanced information about upcoming events provided additional time to drivers to respond to a braking event. This study also finds that there exists a class of drivers for which response times increase as indicated in Figure 6.

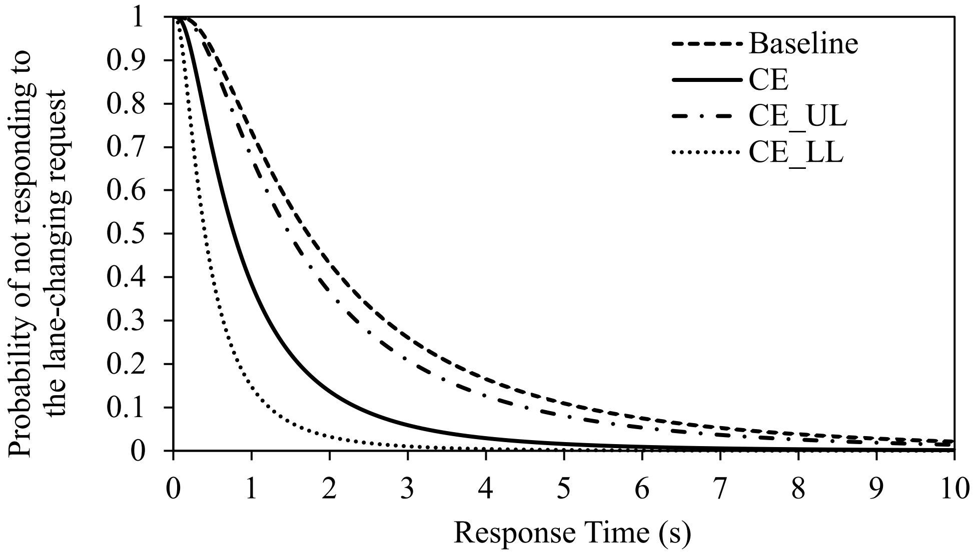


Fig. 10. Response time survival graphs across driving conditions; *CE: mean of the connected environment's coefficient; CE_UL: the upper limit of connected environment's coefficient, i.e., mean + 1.645 × standard deviation; CE_LL: the lower limit of connected environment's coefficient, i.e., mean - 1.645 × standard deviation*

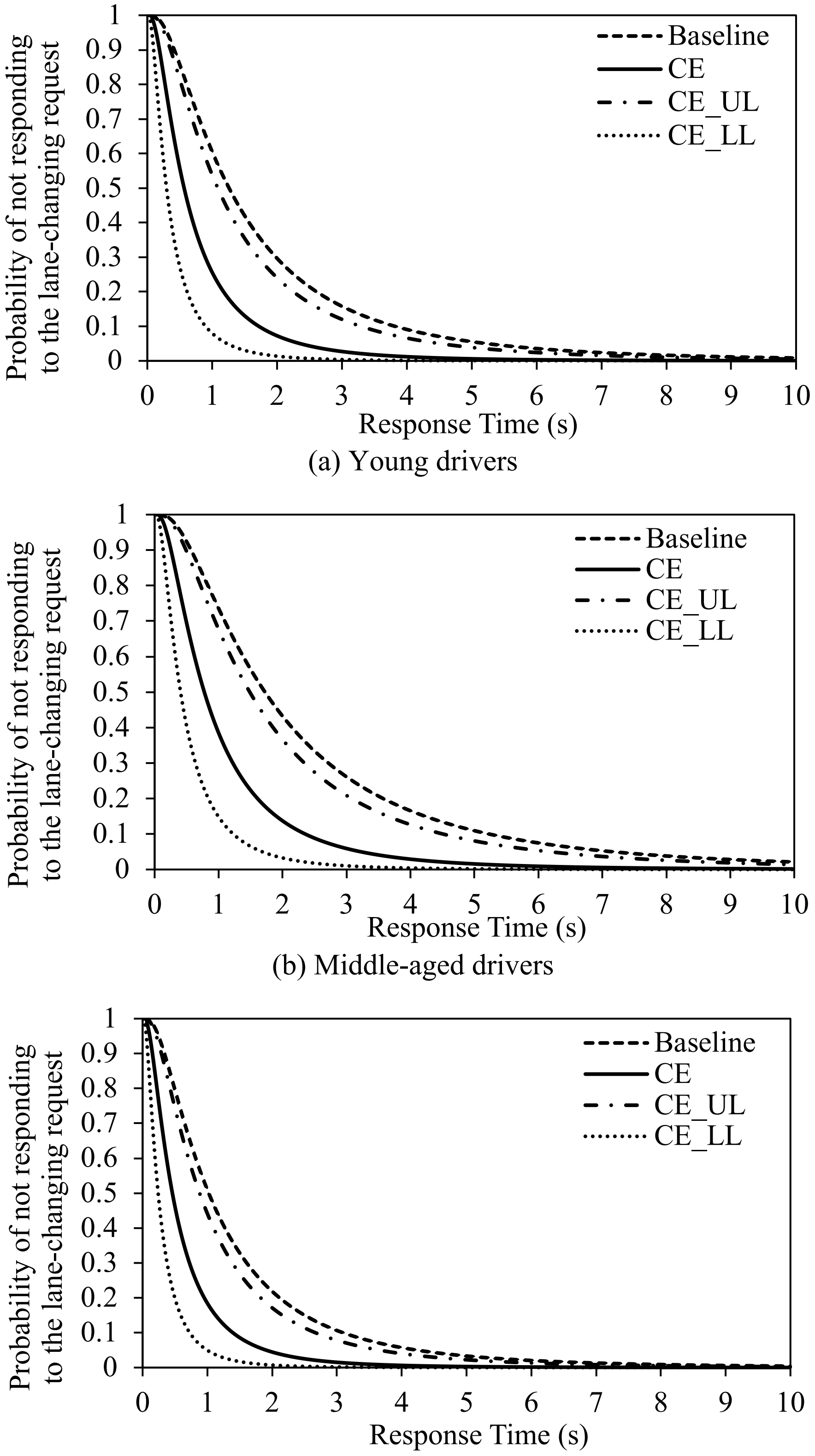
Although car-following and lane-changing are two different driving tasks, response time is a primary component in both these tasks. As such, a comparison of response times during car-following and lane-changing scenarios is conducted. Some representative studies reported that response times are in the range of 0.3 – 1.35 s for car-following in the baseline condition (without driving aids) (Wiese and Lee, 2004, Bella and Russo, 2011, Ruscio et al., 2015). Notably, the response time for lane-changing in this study (in the baseline condition is 1.59 s) is higher than car-following, which is intuitive because in car following the leading vehicle is on the same lane and braking lights are more visible than indicator lights. Similarly, Sharma et al. (2019) reported that the average response time of drivers during car-following in the connected environment is 2.43 s, which is higher than the response time observed for the same drivers during lane-changing in the connected environment, and a possible reason for the higher response time for car following in the connected environment could be the provision of advanced information due to which drivers can obtain more accurate information about the spacing and speed difference between their vehicle and the vehicle in front, and make a better decision without rushing such as delay their responses accordingly as car following is generally less safety-critical than lane changing. Such difference in response time between car following and lane changing underscores the important role the connected environment can play.

5.1.1. Response time and driver demographics

As driving behaviour greatly varies across drivers, this study examines gender and age specific response times, and the corresponding survival graphs are presented in this section.

a) Driver age

Figure 11 presents the survival curves for different age groups. For young drivers, the probabilities of not responding to the lane-changing request in the connected environment scenario at the time intervals 1 s, 1.5 s, and 2 s are respectively 26%, 13%, and 7%. The corresponding probabilities for middle-aged (older) drivers in the connected environment during the same time interval are 39% (18%), 22% (9%), and 14% (4%), respectively.



(a) Young drivers

(b) Middle-aged drivers

(c) Older drivers

Fig. 11. Impact of driver age on response time; *CE: mean of the connected environment's coefficient; CE_UL: the upper limit of connected environment's coefficient, i.e., mean + 1.645 × standard deviation; CE_LL: the lower limit of connected environment's coefficient, i.e., mean - 1.645 × standard deviation*

Compared to the baseline condition, both young and middle-aged drivers tend to have shorter response times during the connected environment scenario, implying that both age groups respond more quickly to the lane-changing request in the connected environment. Young drivers, however, responded faster when they are assisted with driving aids. This finding is consistent with Chen et al. (2011), who reported that the response times of middle-aged drivers under the same driving conditions (i.e., when exposed to in-vehicle information) are longer compared to young drivers. The faster response time of young drivers can be attributed to hypersensitivity associated with their personalities and tendency to follow (or experience) new technologies (Zhao et al., 2019). One of the common examples is use of mobile phone while driving, which is reported to be prevalent among young drivers (Haque and Washington, 2015, Haque and Washington, 2014).

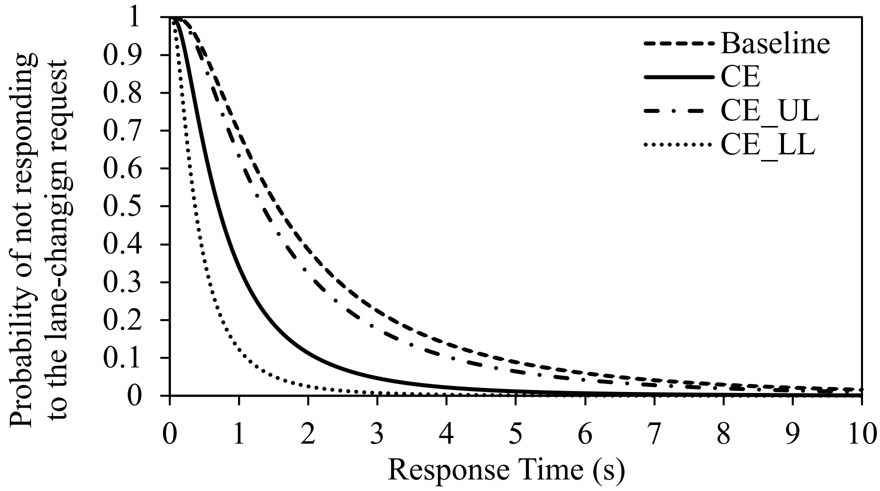
The probability not responding to the lane-changing in the connected environment at the time 1.5 s for older drivers is about 0.8 times lower than the corresponding probability of young drivers, indicating that the response times of older drivers, when they are informed about surrounding traffic, are shorter compared to that of young drivers. On average, older drivers take 0.9 s less time to respond to the lane-changing request compared to that of young drivers. Several studies also reported that older drivers took shorter time to respond compared to that of young drivers (Kramer et al., 2007, Caird et al., 2008, Makishita and Matsunaga, 2008). Kramer et al. (2007) found a longer response time of young drivers compared to older drivers when they were exposed to collision avoiding systems in a simulated driving environment. Similarly, Caird et al. (2008) reported that when drivers (both young and older) receive in-vehicle information about the performance of a signalised intersection, older drivers tend to benefit more from the available information and respond quickly compared to young drivers. Overall, the connected environment benefits both young and older drivers as they both take a shorter time (about 45% less) to respond to the lane-changing request in the connected environment compared to the baseline condition. The shorter response time of older drivers is possibly because they are more cautious and more conservative in order to compensate the negative impact of aging (Zhao et al., 2019), and this is consistent with the study of Kosinski (2008) who reported that response time decreases with increase in age due to their diminishing physiological capabilities.

The survival probability of not responding to the lane-changing request in the connected environment for older drivers at the time 1.5 s is 0.41 times lower than that of middle-aged drivers, implying that middle-aged drivers tend to delay their responses when information is available compared to that of older drivers. Similar findings are reported in the literature (Merat et al., 2005, Chang et al., 2009, Stinchcombe and Gagnon, 2013). Merat et al. (2005) observed that the response times of older drivers when they were exposed to in-vehicle information systems are shorter compared to that of middle-aged drivers driving in the same condition. A possible reason of shorter response times of older drivers compared to middle-aged drivers is less cautious behaviour of middle-aged drivers who tend to rely more on their driving skills (Adebisi et al., 2019). Overall, both (middle-aged and older) drivers decrease their response times in the connected environment compared to when they are driving in the baseline condition.

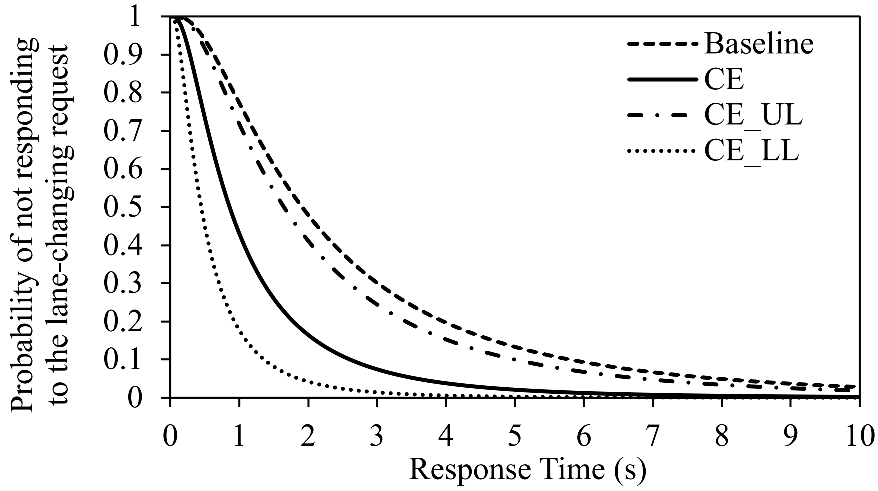
From Figure 11, it can be concluded that although all age groups benefit from the connected environment, there exists differential response time behaviour among different drivers in the connected environment, which is supported by the literature.

b) Gender

Figure 12 displays the survival probabilities of not responding to the lane-changing request for both female and male drivers. In the baseline condition, the probability of female drivers not responding to the lane-changing request at 1.5 s is 52% while the corresponding probability for the male drivers in the baseline condition is 61%, suggesting that female drivers respond more quickly to the lane-changing request compared to their counterpart. This is consistent with past research (Bakowski et al., 2015, Xue et al., 2015), which reported that male drivers tend to delay their responses and are more likely to engage in safety critical events. Meanwhile, the survival probabilities of female drivers not responding to the lane-changing request in the connected environment (and baseline) scenarios at the time intervals of 1 s, 2 s, and 3 s are respectively 34% (70%), 11% (38%), and 5% (22%), while the corresponding survival probabilities for male drivers in the connected environment (and baseline) scenarios during the same time interval are 43% (77%), 15% (48%), and 7% (30%). Roughly, the connected environment increases drivers' probability of responding to a lane-changing request by about 200% for male, and more than 140% for female. This finding reveals that both male and female drivers benefit from the information provided by the connected environment.



(a) Female



(b) Male

Fig. 12. Effect of the connected environment on gender difference; *CE: mean of the connected environment's coefficient; CE_UL: the upper limit of connected environment's coefficient, i.e., mean + 1.645 × standard deviation; CE_LL: the lower limit of connected environment's coefficient, i.e., mean - 1.645 × standard deviation*

Further, we observe that male drivers in the connected environment, on average, take 22% longer to respond to the lane-changing request compared to that of female drivers. This implies that female drivers benefit more from the available information, which agrees with Yan et al. (2014) where male drivers responded late to in-vehicle information and received higher warning alerts. Females, in general, are often good at comprehending the provided information and react accordingly compared to their counterparts (Halpern et al., 2007), and similar behaviour has been observed in the study. Furthermore, male drivers are repeatedly reported to be aggressive (Montgomery et al., 2014, Özkan and Lajunen, 2005, Iversen and Rundmo, 2004, Shinar and Compton, 2004, Hennessy and Wiesenthal, 2001) and are less likely to yield or delay to a lane-changing request compared to female drivers.

6. Conclusions and Future Research Directions

This study investigated drivers' responses to a lane-changing request of the lead vehicle on the adjacent lane in two driving conditions, namely a baseline condition without driving aids and a connected environment with driving aids. Seventy-eight participants from the general population performed two drives in a simulated environment of the CARRS-Q Advanced Driving Simulator. Drivers' responses to the lane-changing request were objectively obtained using the segmentation-based approach that classified a driver's response into three decisions: accelerating to ignore the lane-changing request (i.e., aggressive behaviour), decelerating to show courtesy (i.e., cooperative behaviour), and no response (i.e., remaining unaffected).

Since the definition of response time for the lane-changing decision-making is ambiguous in the literature, this study clearly defined the response time. Furthermore, drivers' response times were modelled using a random parameters AFT hazard-based duration model. The model identified random and non-random parameters. The former includes the parameter for the connected environment dummy variable, while the latter contains parameters for the drivers' initial speed and inserting gap variables as well as driver age and gender. Overall, the drivers in the connected environment are more likely to respond faster to the lane-changing request. The random parameter of the connected environment reveals that not all of the drivers in the connected environment respond faster but a proportion of drivers may take a longer time to respond to the lane-changing request. Moreover, to understand such differential response time behaviour, a decision tree analysis was performed that reveals that a driver's response time generally decreases in the connected environment but may increase if the inserting gap is larger in the connected environment compared to baseline conditions. Older and female drivers are more likely to respond quicker when they are assisted with driving aids compared to their counterparts. Overall, results reveal that drivers in the connected environment (with driving aids) become more cooperative by showing courtesy to the lane-changing request of the lead vehicle while drivers tend to be more aggressive when driving aids are not available. Furthermore, drivers in the connected environment maintain a larger inserting gap (or distance to the lead vehicle on the current lane) and a larger lead gap to lane-changing vehicle from the adjacent lane.

Findings from this study are expected to contribute to improve our understanding of driving behaviour, more specifically, drivers' response times to the lane-changing request. Such understanding can not only assist in improving the design of the connected environment, but also be used to lower risky behaviours of drivers.

Since this study utilises the Advanced Driving Simulator where other traffic is programmed, the impact of faster or slower response time on surrounding traffic could not be determined. Also, the lane-changing request generated by the lead vehicle is again a programmed vehicle and behaves exogenously. In a real-world scenario, a lane-changing request is sometimes generated instantaneously while in other cases drivers also reveal their intensions of lane-changing quite late. Investigating different lane-changing requests and how the connected environment assists drivers in responding to these requests is a question that remains answered and is worth investigating. It is also observed that drivers tend to avert their lane-changing decisions after signalling for a variety of reasons, which can be termed as false lane-changing or failed lane-changing attempt. A driver's response to such failed lane-changing instances is likely to be different from the real ones, and again a topic of interest in the further research. In this study, a random parameter model is estimated. A potential future research direction could be estimating a latent class model, which is often used with limited sample size, and compared with a random parameter model. Although the resulting classes are latent and endogenous, they may indicate two classes in which one responds differently to the connected environment than the other.

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