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A Rear-end Collision Risk Assessment Model based on Drivers' Collision Avoidance Process under Influences of Cell Phone Use and Gender - A Driving Simulator Based Study

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Abstract

Driver's collision avoidance performance has a direct link to the collision risk and crash severity. Previous studies demonstrated that the distracted driving, such as using a cell phone while driving, disrupted the driver's performance on road. This study aimed to investigate the manner and extent to which cell phone use and driver's gender affected driving performance and collision risk in a rear-end collision avoidance process. Forty-two licensed drivers completed the driving simulation experiment in three phone use conditions: no phone use, hands-free, and hand-held, in which the drivers drove in a car-following situation with potential rear-end collision risks caused by the leading vehicle's sudden deceleration. Based on the experiment data, a rear-end collision risk assessment model was developed to assess the influence of cell phone use and driver's gender. The cell phone use and driver's gender were found to be significant factors that affected the braking performances in the rear-end collision avoidance process, including the brake reaction time, the deceleration adjusting time and the maximum deceleration rate. The minimum headway distance between the leading vehicle and the simulator during the rear-end collision avoidance process was the final output variable, which could be used to measure the rear-end collision risk and judge whether a collision occurred. The results showed that although cell phone use drivers took some compensatory behaviors in the collision avoidance process to reduce the mental workload, the collision risk in cell phone use conditions was still higher than that without the phone use. More importantly, the results proved that the hands-free condition did not eliminate the safety problem associated with distracted driving because it impaired the driving performance in the same way as much as the use of hand-held phones. In addition, the gender effect indicated that although female drivers had longer reaction time than male drivers in critical situation, they were more quickly in braking with larger maximum deceleration rate, and they tended to keep a larger safety margin with the leading vehicle compared to male drivers. The findings shed some light on the further development of advanced collision avoidance technologies and the targeted intervention strategies about cell phone use while driving.

Keywords: Rear-end Collision Risk Assessment Model; Cell Phone Use; Driver's Gender; Driving Simulator; Collision Avoidance

1. Introduction

The great and rapid increase of motorization in 21st century aggravates the road traffic congestion and the high-frequency of traffic crashes in many countries on the world. The World Health Organization reported that over 20 million people around the world were injured annually because of traffic crashes and at least five million were disabled for life. In addition, the cost of dealing with the consequences was estimated at billions of dollars (World Health Organization, 2013). Among all traffic crashes, the rear-end crash is the most common type that results in a high proportion of injuries, fatalities and economic loss (Center for Disease Control, 2009). According to the National Highway Traffic Safety Administration (NHTSA) General Estimates System (2012), there were an estimated 1.7 million police-reported rear-end crashes in the United States in 2010, accounting for about 32% of a total of 5.4 million crashes. In China, it was reported that over 40% of highway traffic crashes were rear-end collisions, constituting 47.7% of the economic loss of all traffic crashes (National Traffic Administration Bureau, Ministry of Public Security, 2011). From the perspective of driving performance, the occurrence of a crash and the crash severity are deemed to have a close link with the driver's collision avoidance manoeuvres (Kaplan and Prato, 2012; Bélanger et al., 2015). Taking an effective collision avoidance action in precrash situations may help drivers significantly reduce the collision-involvement risk or minimize the crash severity even if the collision is unavoidable

(Harb et al., 2009). Therefore, deep investigations into the drivers' rear-end collision avoidance process, the behavioral mechanism, as well as the relevant influencing factors are critical for developing effective countermeasures to reduce crash risk and severities.

1.1. Rear-end Collision Avoidance Process

The rear-end crashes have been investigated in different traffic situations by many researchers, including the rear-end collision risk at signalized intersections (Abdel-Aty et al., 2009; Wang and Abdel-Aty, 2006), urban arterials (Das and Abdel-Aty, 2011), urban road tunnels (Meng and Qu, 2012), work zone areas (Meng and Weng, 2011; Weng et al., 2015), and freeway recurrent bottlenecks (Li et al., 2014), etc. Various statistical methods and models based on the crash data were applied or developed to evaluate the rear-end collision risk and/or crash severity, such as the generalized estimation model (Wang and Abdel-Aty, 2006), the inverse Gaussian regression model (Meng and Qu, 2012), the multinomial logit model (Chen et al., 2015), the head kinematic model (Linder 2000), decision table and Naïve Bayes method (Chen et al., 2016), and the generalized nonlinear model (Lao et al., 2014). In order to reduce the occurrence of a rear-end collision, many studies have been conducted to develop the rear-end collision warning systems and technologies (Ito and Osawa, 2015; Bella and Russo, 2011). As most of the rear-end crashes occurred in a car-following situation, a better understanding of the car-following behaviors and decision-making habits is important to seek the optimized car-following strategies for reducing the crash risk during the rear-end collision avoidance period (Broughton et al., 2007; Duan et al., 2013).

The general rear-end collision avoidance process is essentially a consecutive process consisted of risk cognition, judgement and decision-making, and vehicular operation. When a sudden braking manoeuvre of the preceding vehicle occurred, any fault in any step of the process might lead to the occurrence of a rear-end crash, such as delayed risk cognition, wrong judgement and decision making, or inappropriate vehicular operation. Prior researches have pointed out that the main reason of rear-end collisions were that the driver followed a leading vehicle too close and was not able to perceive or react to the actions of the leading vehicle (Knipling et al., 1993). However, among the factors that result in a driver's degraded abilities in the collision detection and avoidance process, the driver distraction was regarded as a primary cause, especially for rear-end crashes (Green and Shah, 2004; Muhrer and Vollrath, 2011). Distracted driving that is defined as a specific type of inattention occurs when drivers divert their attention away from the driving task and towards a competing activity (NHTSA, 2016). Among all of the distracted driving behaviors, the cell phone use while driving is commonly regarded as one of the most serious forms (McEvoy et al., 2005). According to statistics in 2014, there were 2,955 fatal crashes that occurred on U.S. roadways involved distraction (10% of all fatal crashes), 385 fatal crashes reported to have involved the use of cell phones as distractions (13% of all fatal distraction-affected crashes) and a total of 404 people died in fatal crashes that involved the use of cell phones or other cell phone-related activities as distractions (NHTSA, 2016). In addition, driver characteristics (e.g. gender, age and experience) have been identified to be highly associated with the driving performance in traffic crashes (Ye et al., 2015), and the gender played an important role in the traffic crash involvement (Morgan & Mannering, 2011; Storie, 1977). Thus, it was important to examine how these potential factors, such as cell phone use and gender, impacted the rear-end collision avoidance process.

1.2. Effect of Cell Phone Use on Rear-end Crash Risk

The car-following scenario as the most common driving task in the daily drive requires the driver to constantly respond to the surrounding events including the leading vehicle's acceleration and deceleration, and the merging behavior of other vehicles, etc. When drivers are distracted, a reduction in the driver's abilities to properly detect and respond to these events presents a significant threat to safety. The widespread popularity of cell phone in modern society gives rise to this serious safety concern of driver distraction. A number of studies in the simulated situations (Drews et al., 2008; Beede and Kass, 2006) and in the field (Collet et al., 2010a, 2010b) concluded that the use of cell phones while driving has adverse consequences on a driver's probability of being involved in a crash (Collet et al., 2010a, 2010b; Drews et al., 2008; Rakauskas et al., 2004; Strayer and Johnston, 2001). In addition, a large number of studies showed cell phone use might cause operational and/or cognitive interference with the driving task and impair the driving performance in numerous measures. The impaired performances mainly include the increase in reaction time (Strayer and Drews, 2004; Hancock et al., 2003), the deterioration of speed control (Rakauskas et al., 2004; Reimer et al., 2011), the increased variation of lateral control (Dozza et al., 2015; Haque and Washington, 2015), the limitation in the allocation of visual attention (Harbluk et al., 2007; Reimer et al., 2012), and failure to detect relevant traffic signals (Strayer and Johnston, 2001; Wilson et al., 2003).

Public concern about the effect of distraction on driving has led to legislation in some countries/areas (for example Japan, England, China and some states of the U.S) that limit the use of cell phones while driving. The motivation for such legislation may mainly concern about interference caused by holding and dialling a cell phone, so talking on hand-free phones is usually permitted. The reason behind is that using a hand-held phone is deemed to distract drivers more seriously and thus interferes with driving tasks more than using a hands-free phone. In addition, early studies suggested that the manual aspects of cell phone use were the critical determinant of a decrement in driving performance (Drory, 1985). However, recent studies have shown that driving performance is also disrupted by conversations using hands-free devices (Metz et al., 2015; Backer-Grøndahl and Sagberg, 2011). Through the technique of functional magnetic resonance imaging (fMRI), the results showed that the brain activity decreased up to 37% because of the cell phone use, which required brain to process the auditory sentences while driving (Just et al., 2008). Other research also reported that different types of cell phone uses (whether hands-free or hand-held) constituted the same level of safety hazard (Lamble et al., 1999; McEvoy et al., 2005; Horey and Wickens, 2006). Thus, it was suggested that driving impairment due to cell phone use, to a large extent, is a result of cognitive degradation, rather than physical distractions (Backer-Grøndahl and Sagberg, 2011).

With regard to the rear-end crash, cell phone use distraction seems to play a greater role in this type of crash compared with others (Neyens and Boyle, 2007; Saifuzzaman et al., 2015). Based on investigation of the crash risk associated with hand-held and hands-free cell phones use among 4307 drivers, a significant difference in the percentage of cell phone use during the crash was found in a rear-end collision, and the percentage of drivers who reported use of a cell phone was significantly higher than those who did not use a cell phone in the rear-end crash (Backer-Grøndahl and Sagberg, 2011). However, when it comes to the reason behind the high rear-end crash risk when using a cell phone during driving, limited research have been conducted and most of them just attributed the reason to the impaired reaction ability (Lamble et al. 1999; Brookhuis et al., 1994). Therefore, it still remains unclear about the effects of different types of cell phone use (both hands-free and hand-held) on the driver's whole rear-end collision avoidance process, which includes not only the reaction performance, but also the braking manoeuvre as well as the possible risk compensatory behaviors.

1.3. Effect of Gender on Rear-end Crash Risk

Gender has consistently been found to be related to the crash risk and most researches indicated that males were more likely to involve more serious crashes and more traffic violations than females (González-Iglesias et al., 2012; Morgan & Mannering, 2011). Several reasons can possibly explain these gender differences. Firstly, male drivers have more exposure on the road since males drove more than females regardless of the types of vehicles (Jiménez-Mejías et al., 2014; González-Iglesias et al., 2012; Ferrando et al., 1998). According to the U.S. Department of Transportation Federal Highway Administration (Santos et al., 2011), American men drive considerably more miles than American women. On average, man drives 40.9 miles per day while woman drives 31.5 miles, and the gender difference is consistently displayed in all age groups. Secondly, male drivers were associated with more risky behaviors leading to a higher frequency of involvement in traffic crash, such as driving over the speed limit, driving under the influence of alcohol or drug, or running red lights (Ainy et al., 2011; Vardaki and Yannis, 2013; Vassallo et al., 2007). Thirdly, there was a relatively lower use of safety devices among male drivers, such as seat belts (Fernandes et al., 2010). However, female drivers also have some problems in vehicle control and mastering traffic situations (Laapotti et al., 2001, 2003), and are more frequently involved in crashes because of judgment errors (Storie, 1977). In terms of cell phone use while driving, females are more likely to restrict cell phone use than males (Lamble et al., 2002), and males are more confident in vehicle control with the cell phone use (Zhou et al., 2009). Additionally, male drivers tend to underestimate the collision risk associated with cell phone use compared to females (Backer-Grøndahl and Sagberg, 2011; Hallett et al., 2011). Although many studies have identified the gender differences involved in traffic crashes and the attitude preferences towards cell phone use while driving, little research focus on the gender effects in the rear-end collision avoidance performance, especially under the cell phone use conditions. Lonczak et al. (2007) has proposed that tailoring driving-related programs or courses to individuals is crucial, and should include particular emphasis on how males and females approach the high-risk driving situations. Thus, the investigation of gender differences in critical driving situation might help road safety program planners develop better prevention strategies targeting the in-vehicle cell phone users by taking advantage of the distinctive performances when men and women engage in cell phone conversation while driving.

1.4. Motivation and Objective of the Study

Although a number of studies have investigated the rear-end crash risk and/or severity with various methods and identified a variety of performance measures that are impacted by cell phone use distraction and driver gender, there are few studies focusing on the drivers' dynamic behavior mechanism in the rear-end collision avoidance process. More specifically, there is a lack of risk assessment models based on driver's collision avoidance process to quantify the influence of cell phone use and driver's gender on different phases of the rear-end collision risk avoidance process and the related collision risk. A possible reason is that the dynamic behavior mechanism in the rear-end collision avoidance process is difficult to be observed in field, even in the naturalistic driving conditions. Instead, driving simulators can provide an adequate representation of the real world and a relative valid assessment of the factors affecting driving performance measures (Bella and Russo, 2011).

It should be mentioned that there are some general limitations and validation considerations for simulator experiments. One of the major problems is the simulator sickness, which occurs frequently with all driving simulators and particularly among older adult drivers (Trick and Caird, 2011). Another concern with using driving simulators is the simulator validity. It is obvious that driving simulation is not real driving (especially in terms of risk). However, there are still many advantages for the use of an advanced driving simulator over similar real-world or on-road driving research, including experimental control, efficiency, expense, safety, and ease of data collection (Nilsson, 1993). Especially, the driving simulator allows experiments to be conducted in controlled conditions and allows researchers to monitor specific details of driving operations that would be too dangerous to replicate in a real driving situation (Rakauskas et al., 2004). Though the complicated and intricate nature of driving can never be completely replicated in a simulator setting, and the drivers may perceive the driving risk less realistic, from an ethical stand point, the researchers could not put the participants in a real driving situation with any potential collision risk. Thus, the driving simulator becomes a proper tool to be used when possible danger might occur in the experiment. Even if there are some differences between results collected in a real driving situation and on simulated driving, numerous studies have proved that driving simulators provide an adequate representation of the real world and particularly have a relative validity in driving performance studies (Mayhew et al., 2011; Shechtman et al., 2009). In a previous simulator validity study, Yan et al. (2008) investigated if the driving simulator can be developed as a test tool to assess traffic safety at signalized intersections with potential rear-end crash risk. The simulator experiment results showed the similar speed behaviors to the field measures and reflected the crash history trend of the intersection, which proved that the driving simulator experiment in virtual reality can be utilized as a valid tool to identity traffic safety problems at the high risk locations. In addition, Caird et al. (2008) found in a meta-analysis study that the effect of cell phone use on driving performance was not significantly different between laboratory simulators, driving simulators, and on-road studies. Therefore, the driving simulator experiment was conducted in this study.

Accordingly, this driving-simulator-based study is conducted to test driver's rear-end collision avoidance performance under different cell phone use conditions and assess the rear-end collision risk through modelling driver's rear-end collision avoidance process. The research framework of the study is presented in Figure 1 and the specific objectives of this study are: (1) to determine the drivers' collision avoidance mode and the key behavioral performance variables that can be used to explain the dynamic interrelation in the rear-end collision avoidance process based on the data extracted from a driving simulator experiment, in which the driver's rear-end collision avoidance performances are tested under the conditions of no phone, hands-free and hand-held cell phone use respectively; (2) to develop a rear-end collision risk assessment model based on the driver's collision avoidance mode with consideration of factors of cell phone use and driver's gender; (3) to assess the effects of different types of cell phone use and driver's gender on the rear-end collision risk based on the developed rear-end collision risk assessment model.

2. Driving Simulation Experiment for Analyzing Rear-end Collision Avoidance Process

2.1. Experiment Apparatus

The driving simulator located in Beijing Jiaotong University (BJTU) was used in this study, as shown in Figure 2. The BJTU driving simulator was an on-road driving simulator produced by the Realtime Technologies. Inc in U.S. According to the scheme proposed by Saluäär et al. (2000), in which the simulators can be classified into low-level, mid-level, and high-level, the BJTU simulator is one between mid-level and high-level with shaking simulation system and a linear motion base capable of operating with 1 degree of freedom (the rotation of pitch). It is an automatic control vehicle composed of a full-size cabin (Ford Focus) with a real operational interface, environmental noise and vibration system, digital video record system, and the central console. The simulated environment is projected with five screens around the vehicle and thus the drivers can have a front/peripheral field of view of 300 degrees at a resolution of 1400 × 1050 pixels. The simulator lab also provides the software for driving scenario design, virtual traffic environment simulation and virtual road modeling.

2.2. Experiment Scenario Design

Previous studies investigated the effect of cell phone use on driving performance in different road environment, such as rural road (Schlehofer et al., 2010; Nurullah et al., 2013; Haque and Washington, 2015), urban road (Reimer et al., 2011; Nurullah et al., 2013; Haque and Washington, 2015) and highway (Burger et al., 2014; Rosenbloom, 2006; Liu and Lee, 2005), etc. Törnros and Bolling (2006) investigated effects of cell phone conversation on mental workload and driving speed in both rural and urban roads. The results showed that drivers' performance on a peripheral detection task while driving was impaired by cell phone conversation in all environments, and the performance was remarkably poor at the complex urban environment. Besides, some research (Metz et al., 2015; Shaaban, 2013) found that the use of cell phone was more frequent in urban areas compared with rural areas based on naturalistic driving data or observational survey studies. In general, the urban arterials were the rear-end crash prone areas (Das and Abdel-Aty, 2011) and the rear-end crash risk was closely linked to the high driving speed and high vehicle density on the road (Duan et al., 2013). It should be noted that in some cases the speed limit on urban road is comparatively high. For example, for the undivided major road of urban arterials in Canada (Forbes et al., 2012), some urban roads in New Zealand (Forbes et al., 2012) and the urban expressway of China (MHURC, 2012), the speed limit could be up to 80 km/h. Therefore, it is reasonable to infer that the combined effect of more frequent cell phone use and complex urban traffic environment might result in more serious performance degradation for drivers. Thus in the study, a high-risk scenario of rear-end collision was created to investigate the potential effects of cell phone conversation and driver gender on the rear-end collision avoidance performance.

The road network created for this study was a 4 km-long, two-way two-lane road with the speed limit of 80 km/h in urban area, of which contained a combination of straights and gentle horizontal curves. A high-density vehicle flow was designed in the roadway network so that the drivers would operate in a car-following situation without any overtaking maneuver (see Figure 3. a), and the operating speed of the vehicles in the opposing lane on the road was about 40~50 km/h under the condition that the traffic volume was close to capacity, which was nearly down to half of the speed limit. In order to exclude the outside interference, the vehicles included in the traffic flow were only passenger cars and there were no pedestrians crossing or traffic lights on test road segments (see Figure 3. b). The signs included in the scenario were only speed limit sign and curve notice sign. The leading vehicle was located on the straight roadway segment of the driving lane and its speed profile was controlled by sensors which were placed at fixed locations on the driving lane. The simulator driver's operating speed would be essentially depended on the leading vehicle's speed profile (see Figure 3. c).

Four sensors were set on the road in order to make subjects follow the leading vehicle in the car-following situation. The first sensor was triggered by the simulator and the other three were triggered by the leading vehicle. When the simulator passed by Sensor 1, the leading vehicle that stopped in front (about 55 m away from the Sensor 1) would start to move with an acceleration rate of 1 m/s^2 and keep a constant speed after reaching the speed of 50 km/h. The Sensor 2 was placed 520 m away from the Sensor 1 to trigger the leading vehicle to decelerate from 50 km/h to 40 km/h with a deceleration rate of 4 m/s^2 so that the simulator could follow the leading vehicle within a certain distance. The Sensor 3 placed 210 m after Sensor 2 was used to trigger the potential rear-end collision. When the leading vehicle drove through Sensor 3, it would take a sharp deceleration action with a deceleration rate of 6 m/s^2 and its speed would decrease from 40 km/h to 4 km/h. Therefore, the subject needed to react in time to avoid the read-end collision. The Sensor 4 placed 10 m away from Sensor 3 was used to make the leading vehicle drive away with an acceleration rate of 1 m/s^2.

The cell phone used in this study was Nokia E5 with dimensions of 115 mm × 58.9 mm × 12.8 mm. The conversation task during the driving period was a series of unit digit arithmetic calculations played by a sound system installed in the simulator and the drivers should give the right answers after they heard the questions. In the hands-free conversation task, the drivers didn’t need to hold the cell phone but they still needed to answer the questions. An example of arithmetic question was like “What does seven plus nine equal?” The reason why the arithmetic calculations are involved in the driving task was that mathematical problems included computations or recognition of presented digits relative to a memorized numerical set (Hancock et al., 2003). The simple arithmetic problem required driver’s simultaneous storage and processing of information, and thus distracted drivers by increasing their cognitive loads. All arithmetic calculation audios were stored in the simulator and triggered by sensors so that subjects could drive under similar mental workload in the same situation. In the hand-held task, the subjects were asked to hold the cell phone to their ear with one hand and control the steering wheel with the other hand while in the hands-free task the subjects could control the vehicle with both their hands. Moreover, an experimenter outside the simulator would record the answers of the drivers.

2.3. Experiment Procedure and Data Collection

A total of 45 subjects were recruited for this research. Since three subjects could not complete the experiment due to the motion sickness, 42 subjects (21 males and 21 females) finished the experiment successfully. As mentioned above, the simulator sickness occurs particularly among older adult drivers (Trick and Caird, 2011). In order to enhance the feasibility of subject recruitment and the quality of data collection, driver age was not focused on in the study. Thus, only the young mature drivers aging from 30 to 40 were recruited for the experiment. The average age of subjects was 35 with a standard deviation of 3 years. Each subject held a valid driver's license and had at least two years of driving experience. Upon arrival, each subject was briefed on the requirements of the experiment and asked to read and sign an informed consent form. The subjects were then advised to drive as they normally did in real-life situations. Before the formal test, each subject performed a practice drive of at least 5 minutes to become familiar with the driving simulator (with automatic transmission). In this practice session, the subjects exercised maneuvers including straight driving, acceleration, deceleration, left/right turn and other basic driving behaviors, and they also exercised the use of cell phone while driving. In addition, subjects were also notified that they could quit the experiment at any time in case of motion sickness or any kind of discomfort.

During the experiment, each subject was required to drive in three scenarios: a baseline scenario (no phone conversation), a hands-free phone scenario and a hand-held phone scenario. In each test scenario, the leading vehicle's type, color, and speed-change profile remain the same so as to exclude the confounding effects potentially introduced by the factors. Since an emergent rear-end scenario is a small-likelihood event during a short time period in reality, several measures were taken to reduce drivers' learning effects and discourage subjects from speculating about the experiment's purpose. Firstly, after each test subjects had a rest for at least 10 minutes. Secondly, before subjects entered the test segments and encountered the designed car-following situation, subjects drove the simulator to pass through several intersections and two short curve segments for enriching the subjects' driving experience. Thirdly, before subjects entered the test segments, some ambient vehicles were arranged to travel in front of the simulator and drove away at intersections. Finally, in order to eliminate the experiment order effect, subjects needed to perform the three tests in a random sequence. In addition, the simulator data were sampled at 60Hz and the hypothesis testing in this study was based on a significance level of 0.05.

3. Rear-end Collision Risk Assessment Model Development

3.1. Model Framework

In the process of rear-end collision avoidance, drivers modulated their speeds by changing the acceleration rate in response to the dynamic speed change of leading vehicle. Thus, the headway distance between the simulator and the leading vehicle changed and a minimum headway distance existed in the rear-end collision avoidance process. The minimum headway distance is not only used to estimate the occurrence of a collision between the simulator and the leading vehicle, but also used as a safety threshold reflecting the temporal buffer that drivers allow themselves for interaction with the leading vehicle. Typical examples of drivers' acceleration rate and headway distance changes were shown in Figure 4. These examples exhibited a clear and uniform rear-end collision avoidance mode, in which the rear-end collision avoidance process could be mainly divided into three stages (see Figure 5):

(1) Stage 1：the brake response stage. This stage started from the time when the leading vehicle decelerated, and ended as the subject started to brake. The duration time of this stage was t_r, which was called brake reaction time. In general, the subject kept a constant initial speed during this period.

(2) Stage 2：the deceleration adjusting stage. In this stage, subjects perceived the collision risk caused by the leading vehicle's sudden brake and they started to reduce their speeds by increasing the deceleration rate to the maximum. The duration time of the stage was t_1, and the deceleration rate in this stage can be assumed to increase linearly.

(3) Stage 3：the maximum deceleration stage. In this stage, subjects kept the maximum deceleration rate (a_m) until they could make sure that they wouldn't have a rear-end collision. Then, they started to decrease the deceleration rate. The duration time of this stage was t_2.

Based on the rear-end collision avoidance mode, the key variables in the collision avoidance process and the interrelation of them were summarized and shown in Figure 6. The initial input variables included three aspects: the subject's operating status (the initial speed and headway distance), the external interfering factors (such as cell phone use) and the drivers' characteristics (such as gender). The driver's brake reaction time (t_r) could be influenced by all these factors. In addition to the brake reaction time, the time to collision (TTC, indicating the degree of rear-end collision emergency) when drivers started braking, as well as the external interfering factors and the drivers' characteristics, could jointly determine the driver's collision avoidance maneuver, such as the length of t_1 and the value of a_m. The minimum headway distance between the simulator and the leading vehicle during the rear-end collision avoidance process was the final output variable which can be used to measure the rear-end collision risk and judge whether a collision occurred. Based on the rear-end collision avoidance mode and the inter-relation of key variables, the framework of the rear-end collision risk assessment model was presented as followings:

$$\mathrm{D}_{min} = \mathrm{Min\ D}(t) \tag{1}$$

$$\mathrm{D}(t) = D_s + \int_0^t V_L(t) - V_F(t)dt - \mathrm{L}v \tag{2}$$

$$V_L(t) = \begin{cases} V_{LS} + a_{LS}t, t \in (0, t_d) \\ V_{LE} + a_{LE}t, t \in (t_d, t_r + t_1 + t_2) \end{cases} \tag{3}$$

$$V_F(t)=\begin{cases} V_{FS}, t\in(0,t_r) \\ V_{FS}+a_m\dfrac{(t-t_r)^2}{2t_1}, t\in(t_r,t_r+t_1) \\ V_{FS}+\dfrac{a_m t_1}{2}+a_m(t-t_r-t_1), t\in(t_r+t_1,t_r+t_1+t_2) \end{cases} \tag{4}$$

$$a_F(t)=\begin{cases} 0, t\in(0,t_r) \\ a_m\left(\dfrac{t-t_r}{t_1}\right), t\in(t_r,t_r+t_1) \\ a_m, t\in(t_r+t_1,t_r+t_1+t_2) \end{cases} \tag{5}$$

$$t_d=\frac{V_{LS}-V_{LE}}{a_{LS}} \tag{6}$$

$$TTC=D(t)/\left|V_L(t)-V_F(t)\right| \tag{7}$$

In which,

D_{min}: minimum headway distance between the simulator and the leading vehicle during the rear-end collision avoidance period

$D(t)$: headway distance at time t during the rear-end collision avoidance period

D_s: initial headway distance when the leading vehicle began to decelerate

Lv: length of the simulator vehicle, which is 4 m in this experiment

$V_L(t)$: speed of the leading vehicle at time t

V_{LS}: speed of the leading vehicle before its deceleration

V_{LE}: speed of the leading vehicle after its deceleration

$V_F(t)$: simulator's speed at time t

V_{FS}: initial speed of the simulator when leading vehicle began to decelerate

a_{LS}: deceleration rate of leading vehicle

a_{LE}: acceleration rate of leading vehicle

$a_F(t)$:driver's deceleration at time t

a_m: driver's maximum deceleration

t_r: driver's brake reaction time, which is also the time duration of stage 1

t_1: time duration of deceleration adjusting stage (stage 2)

t_2: time duration of maximum deceleration stage (stage 3)

t_d: time duration of the leading vehicle's deceleration period

TTC: time to collision at time t

3.2. Model Development and Parameters Estimation

In this study, the generalized linear model (GLM) was used to quantify the relationships between the dependent variables (t_r, t_1, and a_m) and the explanatory variables (i.e. initial speed V_{FS}, initial headway distance D_s, cell phone use and driver's gender). Generalized linear models are extensions of traditional linear models and they are a large class of statistical models for relating responses to linear combinations of predictor variables (Vargas et al., 2014). The GLM was chose mainly because the explanatory variables in the study included both classification variables and continuous variables, and the GLM can link them together when relating one or several continuous dependent variables to one or several independent variables. Besides, the GLM also allows the response probability distribution to be any member of an exponential family of distributions. In general, the main feature of the GLM is that it covers all different situations by allowing for response variables that have arbitrary distributions (rather than simply normal distributions), and for an arbitrary function of the response variable (the link function) to vary linearly with the predicted values (rather than assuming that the response itself must vary linearly). Thus, many useful statistical models can be formulated as generalized linear models by the selection of an appropriate link function and response probability distribution. In the study, each dependent variable including t_r, t_1, and a_m was analyzed with two generalized linear models. One considered driving behavior parameters only as the explanatory variables (e.g. initial speed V_{FS} and initial headway distance D_s,) and the other contained both driving behavior parameters and the influencing factors (cell phone use condition and driver's gender).

3.2.1. Brake Reaction Time (t_r)

Driver's brake reaction time is one of the most often reported performance detriments as a result of cell phone distraction. The GLM results (see Table 1) with driving behavior parameters without considering the influencing factors showed that the driver's brake reaction time was significantly influenced by the driver's initial speed (V_{FS}) and initial headway distance (D_s), and the goodness of fit value (R^2) was 0.513. The GLM results considering influencing factors showed that in addition to V_{FS} and D_s, the driver's brake reaction time was also significantly influenced by the different cell phone use conditions (C), driver's gender (G), and the interaction terms between cell phone use conditions and initial headway distance ($C \times D_s$) and driver's gender and initial headway distance ($G \times D_s$). Adding influencing factors into the model increased the goodness of fit value (R^2) up to 0.622. The estimated function of t_r with driving behavior parameters only was listed in Equation 8 and the function with both behavior parameters and influencing factors was listed in Equation 9, respectively based on the GLM results.

The relationships between t_r and the driving behavior parameters indicated that the driver's brake reaction time decreased with the increase of initial speed and the decrease of initial headway distance (Figure 7. a and b), suggesting that the drivers' alertness would be enhanced with the increase of the potential driving risk. The possible explanation is that as the driving speed increased and the headway distance decreased, drivers were more likely to keep a stable view of the leading vehicle as their main visual focus, and thus their perception abilities on the speed change of the leading vehicle were enhanced.

The interaction effects between influencing factors and behavior parameters (Figure 7. c and d) showed that when the initial headway distance was large enough, drivers without cell phone use had a shorter reaction time than those using a cell phone (both hand-held and hands-free). In addition, it was also found that female drivers showed a shorter reaction time than male drivers. However, when the initial headway distance was comparatively small, the drivers' brake reaction time of those using a cell phone while driving became shorter compared to drivers without using a cell phone and the brake reaction time of male drivers also became shorter than the female drivers. The results implied that the cell phone use led to the drivers' slowly responding to the leading vehicle's speed change when the headway distance was large enough. However, when the situation became emergent with a relatively short headway distance, the drivers with the cell phone use could make a quick attention switch from the secondary task to the driving task, probably because of the awareness of the cell phone use's negative effect on the safety (Dozza et al., 2015). The findings imply that female drivers would be more reactive to the leading vehicle's speed change at long car-following distances than male drivers while male drivers would be more sophisticated to deal with emergent situations than female drivers in the dangerous situation.

$$t_r = -0.215 * V_{FS} + 0.033 * D_S + 2.53 \qquad (8)$$

$$t_r = -0.49 * C_1 - 0.325 * C_2 - 0.281 * G - 0.206 * V_{FS} + 0.013 * D_S + 0.015 * C_1 * D_S + 0.012 * C_2 * D_S + 0.011 * G * D_S + 3.02 \qquad (9)$$

In which,

G: driver's gender, $G = 0$ represents female driver, $G = 1$ represents male driver

C: cell phone use conditions, $C_1 = 0$ & $C_2 = 0$ represents no phone condition, $C_1 = 1$ & $C_2 = 0$ represents hands-free condition, $C_1 = 0$ & $C_2 = 1$ represents hand-held condition

3.2.2. Deceleration Adjusting Time (t_1)

The GLM results of driver's deceleration adjusting time were shown in Table 2. The goodness of fit values (R^2) of the GLM with and without considering influencing factors was 0.534 and 0.459 respectively. The estimated function of t_1 with driving behavior parameters only was listed in Equation 10 and the function with completed explanatory variables was listed in Equation 11. The effects of cell phone use conditions, driver's gender, driver's brake reaction time and TTC, as well as cell phone use × brake reaction time, cell phone use × TTC, driver gender's × brake reaction time, driver gender's × TTC, and brake reaction time × TTC were found to be significant. Without considering the influencing factors, the driver's deceleration adjusting time increased with the increase of brake reaction time and TTC (see Figure 8. a and b). Thus, it can be inferred that the increasing risk of the potential collision (indicated by shorter TTC) would motivate the drivers to be more decisive in braking.

For the drivers without cell phone use, the deceleration adjusting time decreased with the increase of brake reaction time while it increased as TTC increased (see Figure 8. c and d). In the cell phone use conditions, the tendency of deceleration adjusting time was quite different from the no phone condition and even opposite in the hands-free condition, implying that the conversation task and the mental workload caused by cell phone use disturbed driver's deceleration maneuver. Regarding to driver's gender, female drivers had an increased proclivity of quickly braking than male drivers when they reacted late or in urgent situations because the deceleration adjusting time of female drivers became smaller than male drivers when the brake reaction time increased or when the TTC decreased (see Figure 8. e and f).

$$t_1 = 0.132 * t_r + 0.041 * TTC - 0.021 * t_r * TTC + 0.967 \tag{10}$$

$$t_1 = -0.31 * C_1 - 0.101 * C_2 - 0.426 * G - 0.565 * t_r + 0.195 * TTC + 0.76 * C_1 * t_r + 0.463 * C_2 * t_r - 0.128 * C_1 * TTC \\ -0.118 * C_2 * TTC + 0.579 * G * t_r - 0.093 * G * TTC - 0.044 * t_r * TTC + 1.315 \tag{11}$$

3.2.3. Maximum Deceleration Rate (a_m)

Table 3 showed parameter estimates of GLM for the driver's maximum deceleration rate. The goodness of fit values (R^2) of the GLM with and without considering influencing factors was 0.717 and 0.578 respectively. The estimated function of a_m with driving behavior parameters only was listed in Equation 12 and the function with all explanatory variables was listed in Equation 13. As illustrated in Figure 9. a and b, the driver's maximum deceleration rate increased with the decrease of brake reaction time and TTC. For drivers who had a shorter brake reaction time, the maximum deceleration rate in no phone condition was slightly larger than that in cell phone use conditions (see Figure 9. c). However, for drivers who had a relatively longer brake reaction time, the maximum deceleration rates in cell phone use conditions were obviously larger than that in no phone situation. In addition, the results also indicated that when the TTC was small, the maximum deceleration rate in the hand-held condition was obviously larger than that in both hands-free cell phone use and no phone use conditions (see Figure 9. d). The driver's gender was also a significant factor that affected the maximum deceleration rate. Especially when the brake reaction time was small, female drivers seemed to have a larger maximum deceleration rate than male drivers (see Figure 9. e).

$$a_m = 2.253 * t_r + 0.668 * TTC - 0.158 * t_r * TTC - 10.501 \tag{12}$$

$$a_m = 1.718 * C_1 + 0.636 * C_2 + 1.755 * G + 3.982 * t_r + 0.726 * TTC - 0.921 * C_1 * t_r - 1.83 * C_2 * t_r - 0.155 * C_1 * TTC + 0.344 * C_2 * TTC - 0.737 * G * t_r - 0.158 * t_r * TTC - 13.147 \tag{13}$$

Overall, the above statistical models developed in the study present the driver's behavioral mechanism in a rear-end collision avoidance process and reveal the inter-relationship of the key variables that reflect the collision avoidance performance. Understanding the driver's behavioral mechanism was crucial to identify appropriate countermeasures for traffic crashes. Thus, the findings shed some light upon the development of the crash avoidance warning and control intervention systems to enhance driving safety.

3.3. Model Solution and Validation

The flow diagram of the model algorithm was shown in Figure 10. Given a definite cell phone use condition, driver's gender, driver's initial speed and headway distance, the driver brake reaction time (t_r) could be computed by Equation 8 and the TTC after the driver's reaction could be obtained by Equation 7. Thus, the values of deceleration adjusting time (t_1) and maximum deceleration (a_m) could be calculated through Equation 9 and Equation 10 respectively. The precondition of acquiring the headway distance between the simulator and the leading vehicle was to compare the driving status of them, which means comparing the leading vehicle' deceleration duration time (t_d) with the driver's brake reaction time (t_r) and the deceleration adjusting time (t_1). When the leading vehicle finished its deceleration, the simulator driver could be in any stage, such as the brake response stage, the deceleration adjusting stage or the maximum deceleration stage. The specific equations of computing the headway distance between the leading vehicle and the simulator were different with different stages. The time iteration frequency was 0.01s, so the headway distance was calculated 100 times in a second. The maximum iteration cycle were set 6000, which could ensure that it was longer than the duration of the collision avoidance process. Finally, the minimum headway distance between the simulator and the leading vehicle in the collision avoidance process was obtained.

In order to validate the model, the relative absolute error (RSE) was calculated to measure the difference between the minimum headway distance predicted by the model and the minimum headway distance obtained by the experiment data (see Equation 14). The average values of the minimum headway distance for the experiment data and prediction results were 15.85 m and 15.64 m, respectively (as shown in Table 4), and the average value of the relative absolute error was 3.55 m. Figure 11 showed the relationship between the experiment data and the prediction results, which could conclude that the prediction results were significantly associated with the experiment data. In addition, the R^2 value for the model was 0.833, which means that 83.3% of the variability in the experiment data could be explained by the variation in the prediction results. Consequently, the validation index indicated that the model developed in this study had a good prediction performance.

$$RSE = \frac{1}{n}\sum_{i=1}^{n}\left|D^{i}_{\min(E)} - D^{i}_{\min(M)}\right| \tag{14}$$

In which,

n represents the number of subjects; $D_{min(E)}$ represents the minimum headway distance obtained by the experiment data; $D_{min(M)}$ represents the minimum headway distance predicted by the model.

4. Influences of Cell Phone Use and Gender on the Rear-end Collision Risk

Among the 126 sample data collected in the study, seven rear-end collisions were observed including two female drivers and five male drives. As for the cell phone use, four of them happened in the hands-free cell phone use condition and the other three happened in the hand-held cell phone use condition. In addition to the collision cases, the near-collision cases were also identified in the study based on the minimum headway distance results (in the near-collision cases, the minimum headway distances were smaller than 5 m). There were 15 near-collisions occurred during the experiment (7 females vs. 8 males, 3 no phone vs. 7 hands-free vs. 5 hand-held). According to the minimum headway distance distribution showed in Figure 11, the collision and near-collision cases were found to be comparatively concentrated, which indicated that the model had particularly good prediction performance on the group with high collision risk.

In the correlation test, the collision or near-collision occurrence had no significant correlation with the different types of cell phone use conditions and the driver's gender, but the use of cell phone or not was found to be a significant factor for the near-collision occurrence (Pearson Correlation = 0.195, P = 0.026) and a nearly significant factor for the collision occurrence (Pearson Correlation = 0.165, P = 0.061). Apart from the collision results, the key behavioral variables and the minimum headway distance in the collision avoidance process could be also used to assess the driver's rear-end collision risk.

4.1. Assessment on Influence of Cell Phone Use

The rear-end collision risk assessment model developed in this study provided the value of the minimum headway distance between the simulator and the leading vehicle under different situations. Figure 12 showed the relationship among the minimum headway distance, the initial speed as well as the initial headway distance for drivers of different genders under different cell phone use conditions. First of all, the minimum headway distance decreased with the decrease of the initial headway distance and it also decreased as the initial speed increased. It was notable that when the initial headway distance was under 10 m, the minimum headway distance in all different conditions would drop to 0, which means a rear-end collision would happen. In addition, it was found that there were no obvious differences in the minimum headway distances among different cell phone use conditions when the initial headway distance was small. However, larger differences could be observed as the initial headway distance increased and the minimum headway distance under the no phone condition tended to be larger than those under cell phone use conditions (Figure 12. a). In addition to the minimum headway distance, cell phone use also had significant effects on the driver's brake reaction time, deceleration adjusting time and maximum deceleration in the rear-end collision avoidance process according to the generalized linear model results.

The brake reaction time has been widely used as a surrogate measure of the crash risk of cell phone distraction under various study situations, including laboratory, driving simulator, and field study. Previous studies about cell phone use while driving have shown an increase in the braking reaction time in response to sudden events such as initiation of brake lights of a leading vehicle (Alm &Nilsson, 1995; Brookhuis et al., 1994). Consiglio et al. (2003) examined the braking response of distracted drivers upon the activation of a red lamp in a laboratory setting and found that both hands-free and hand-held phone conversations resulted in a slower response in performing the braking task. Similarly, a meta-analysis reported a 0.25 s increase in the reaction time for all types of phone-related tasks and concluded that both hands-free and hand-held phone conversations had negative effects on the reaction time (Caird et al., 2008). In addition, slower responses of distracted drivers were also observed in a desktop simulator experiment, where drivers tended to take one-third of a second longer to begin driving from a stop sign while engaged in a phone conversation (Beede and Kass, 2006). In this study, it was found that the driver's brake reaction time in different cell phone use conditions was significantly related to the initial headway distance between the simulator and the leading vehicle. When the initial headway distance was large, the brake reaction of no phone use drivers was faster than the cell phone use drivers, which is consistent with previous research achievements. However, when the initial headway distance became smaller, the cell phone users tended to react faster than the normal drivers. This interesting finding proved that cell phone use drivers were partly aware of the risk of cell phone use while driving. Especially in the urgent situation, the alertness in mind urged the drivers to switch their attention from the secondary task to the main driving task quickly when faced with potential collision risk.

In the deceleration adjusting stage, the length of the deceleration adjusting time could represent the extent of driver's decisiveness in implementing deceleration action. The experiment results showed that the earlier reaction drivers with cell phone conversations appeared to be more decisive in taking deceleration action since they spent less time in reaching the maximum deceleration rate than those who did not use cell phones. The finding suggested that the cell phone use drivers might compensate for their increased sense of risk by decelerating more rapidly while driving. In contrast, for late reaction drivers, the deceleration adjusting time was much longer in cell phone use conditions compared to the no phone use condition, and the same phenomenon appeared when TTC was small. Therefore, it could be inferred that the cell phone conversation might constitute an obstruction in the collision avoidance decision execution for the drivers who were in high-risk circumstances. This inferior performance also demonstrated that, although drivers could switch attention between tasks, there appears to be an upper limit to available cognitive processing within the context of maintaining vehicle control (Liu and Lee, 2005).

In the maximum deceleration stage, the cell phone use drivers were more likely to have larger maximum deceleration rates when they were in an emergency, especially for the hand-held cell phone use drivers. The large variation in braking demonstrated that distracted drivers—often being delayed in monitoring, gathering and integrating appropriate information about speed, distances and other stimuli related to driving—might brake harder to compensate for the delay in initiating braking (Harbluk et al., 2007). Similarly, Hancock et al. (2003) found that distracted drivers were slower in response to a change of a traffic light from green to red and subsequently braked more intensely in compensation. Another driving simulator study examined the effects of hand-held, hands-free cell phones and hands-free voice device on various driving performances including the deceleration rate in response to sudden brakes of a leading vehicle (Benedetto et al., 2012). It was found that the use of all cell phone devices led to an increase of the average deceleration as a compensation for the delay in response time due to cell phone conversation. In an on-road experiment study, Harbluk et al. (2007) reported that there were more occasions of hard braking with the longitudinal acceleration exceeding 0.25 g in demanding cognitive task condition when drivers were required to solve the mathematics problems while driving.

On the whole, results of the study demonstrated the effect of cell phone use on driver's collision avoidance performance and the collision results. Even though the drivers could be aware of the potential negative effect of cell phone use on the safety and took a series of compensation behaviors to mitigate the risk, such as the shorter reaction time and the larger maximum deceleration rate in critical situation, the cell phone use drivers still encountered higher risk than the drivers without using cell phones, which were estimated by more collision/near-collision cases and smaller minimum headway distance.

More importantly, this study also demonstrated the collision avoidance behavior differences between hands-free and hand-held cell phone use. Since many governments have introduced legislation banning only for the use of hand-held cell phone while driving, but allowed the use of hands-free technology for conversing. However, the present study identified that the driver's rear-end collision avoidance performance was also disrupted by the hands-free cell phone conversations, and the risk of the rear-end crash with hands-free cell phone use was almost the same as hand-held cell phone use. On one hand, the experiment result showed that collisions or near-collisions in cell phone use conditions were not significantly different between the hands-free and hand-held mode; on the other hand, the collision avoidance behaviors appeared to be quite different between hands-free condition and hand-held condition. Firstly, the brake reaction of hands-free cell phone users was a little faster than that of the hand-held cell phone users. However, once drivers noticed the potential collision risk, the hand-held cell phone users took more decisive deceleration maneuver. Meanwhile, for drivers in emergency situation, hand-held cell phone users also took larger maximum deceleration than the hands-free cell phone users. These compensation behaviors explained the phenomenon in Figure 12. a that the minimum headway distance of hand-held users was slightly larger than that of the hands-free users, and it is also consistent with the previous findings that conversations via hand-held phone appeared to trigger slightly larger compensatory behavior than in the hands-free condition (Ishigamiand Klein, 2009; Haque and Washington, 2015). In other words, drivers appeared to estimate the risk associated with conversations less when they engaged in hands-free conversations. Reimer et al. (2011) found that using a hands-free cell phone could be even more dangerous than using a hand-held phone since drivers tried to compensate for the risk in the latter case but forgot to do it in the hands-free phone situation. Ishigami and Klein (2008 & 2009) also found that drivers might compensate for the deleterious effects of cell phone use by decreasing their speed when using a hand-held phone while neglect to do so when using a hands-free phone. Lesch and Hancock (2004) believed that the driver’s priori confidence in his/her ability to deal with distracters (i.e., cell-phone use) might impact decisions to engage in compensatory behaviors. Therefore, all of the findings raised a serious question on the appropriateness of existing legislations about the use of cell phones while driving and it was suggested for the legislative bodies to consider these evidences when examining cell phone use laws that impose bans on the use of hand-held phones yet permit the use of hands-free devices.

4.2. Assessment on Influence of Gender

With regard to the behavioral performances in the collision avoidance process, female drivers reacted faster than male drivers when they kept an appropriate car-flowing headway distance. However, as the initial headway distance decreased, the respond ability of female drivers seemed to be inferior to male drivers as the brake reaction time of female drivers turned to be larger than that of male drivers. Research of Hancock et al. (2003) covering the effects of gender showed that cell phone distraction had a greater influence on females than males with corresponding impairments on the reaction time of 0.25 s and 0.14 s, respectively. In the deceleration adjusting stage, female drivers tended to take more intense braking with smaller deceleration adjusting time than male drivers when they were in emergency condition. Moreover, the maximum deceleration rate of female drivers was generally larger than male drivers.

In contrast, male drivers reacted slower than female drivers when the initial headway distance was comparatively large. Even in the emergency situation, male drivers still spent longer time in decelerating while reaching a smaller maximum deceleration than female drivers. The behavioral performances may explain in part why the minimum headway distance of male drivers was generally smaller than female drivers in different cell phone use conditions (see Figure 12. b). Meanwhile, the results also indicated that male drivers perceived the risk differently than female drivers, and they tended to take more risks such as reducing safety margin with hazard in front. Previous research has reached consensus in that male drivers tended to be more aggressive in driving compared with female drivers (Qu, et al., 2015) and drivers with aggressive dispositions might expect an erosion of safety margin (Hancock et al., 2003).

The results in the study reflected some gender differences in driving risk perception and response under a critical situation while following a leading vehicle. They may provide meaningful references for the traffic operation or driving behavior modelling to take the driver characteristic as a reasonable factor into account, and inspire considering the gender factor into the training program for novice drivers or the development of crash avoidance warning system.

Overall, it should be noted again that the model framework proposed in the study not only demonstrated the inherent behavioral mechanism of a rear-end collision avoidance process, but also assessed the effects of cell phone use and driver's gender on collision avoidance behaviors. Furthermore, the model framework was not restricted to the two factors in this study, meaning that the framework had a good expandability to other driving intervention factors (for example, alcohol use and weather condition) and driver characteristic (e.g. age and experience), with which the manner and extent that these factors affect driving performance in collision avoidance can be clarified. Moreover, since it was proved that this study provided a measurable safety evaluation model with high prediction accuracy, the model framework could also be applied for other types of collisions (e.g. right-angle collision and head-on collision) as well as the existing car-following models to better reproduce traffic dynamics with consideration of various human factors' implications on road safety and/or operations.

5. Conclusion and Limitation of the Study

Traffic crash occurs infrequently for a driver in daily drive. However, the collision avoidance behavior is much more common for drivers, relying on their reaction, decision-making and decision execution abilities. If drivers could perceive the collision risk timely and take appropriate collision avoidance maneuver, it is very likely to avoid the collision or reduce the severity and damage even if the collision is inevitable. In summary, this study investigated the rear-end collision avoidance performance of drivers in the high-fidelity driving simulator and developed a rear-end collision risk assessment model under the influence of cell phone use and driver's gender. In the driving simulator experiment, drivers needed to respond to a sudden deceleration of the leading vehicle in a car-following situation. The model developed based on the driving simulation experiment data was found to quite reasonably demonstrate the driving behavior mechanism of the rear-end collision avoidance process. The results identified the significant effects of cell phone conversation and driver's gender on the rear-end collision avoidance behaviors, including the brake reaction time, the deceleration adjusting time and the maximum deceleration rate. Although compensatory behaviors of cell phone use drivers were examined as they attempted to reduce the workload, the collision risk of cell phone use drivers was still higher than that of no phone use drivers. More importantly, the results supported the notion that the use of hands-free phones impaired driving performance on the rear-end collision avoidance in the same way as the use of hand-held phones, indicating that the driving impairment to a large extent was a result of cognitive degradation, rather than physical distractions. It is therefore recommended that drivers do not engage in any cell phone use (either hand-held or hands-free) while driving, particularly under the critical situations. As for the gender effect, the results indicated that female drivers had longer reaction time than male drivers in critical situation, but they were more quickly in braking with larger maximum deceleration rate, and thus kept larger safety margin with the leading vehicle compared to male drivers. Overall, the present study provided an alternative and probable paradigm for measuring the effect of intervention factors and driver characteristics on on-road collision avoidance performances.

However, there are still some limitations in the study that need to be pointed out. Firstly, the speed and deceleration rate of the leading vehicle should also be important factors that could influence the drivers' collision avoidance performance. However, the two variables were constant in this study as the drivers were assumed to be in the circumstances with same level of rear-end collision risk. Further investigation will consider to design the leading vehicle's different deceleration operations and incorporate them as an influencing factor into the rear-end collision risk assessment model. Secondly, the conversation contents used in the experiment were simple arithmetic questions, which might be different with the daily drive situation. According to a previous study of Horey and Wickens (2006) that compared 15 experiments involving a real conversation and 22 experiments using various information processing tasks, it was found that the effects of both types of tasks were significant in producing errors in driving performance, and the costs were even higher for actual conversation than for other information processing tasks. It is therefore likely that our arithmetic question task underestimates the deterioration of driving performance that would result from actual cell phone conversations. Besides, there were also studies that suggested the intensity of the phone conversation is important, with more intense conversations adversely affecting driving performance (Briem and Hedman, 1995; Dula et al., 2011). Therefore, the comparison of rear-end collision avoidance performances under distractions caused by arithmetic questions and real conversations, or intensifying the driver's cognitive loads by increasing the complexity of arithmetic problems could be one of the focus in future study. Thirdly, the model developed in the study was based on the driver's behaviors in the rear-end collision avoidance process. More simulation experiments of different types of collisions (e.g. right-angle collision and head-on collision) will be conducted in future study to test the usability of the model framework on the other types of collisions.

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Table 1: Generalized linear model results of the brake reaction time

Parameter	Driving Behavior Parameters					R^2
	B	**Std. Error**	**Wald Chi-Square**	**df**	**Sig.**	
Initial Speed (V_{FS})	-.215	.0486	19.639	1	.000	
Initial Headway Distance (D_s)	.033	.0018	335.889	1	.000	**0.513**
(Intercept)	2.530	.5272	23.040	1	.000	
Parameter	**Considering Influencing Factors**					**R^2**
	B	**Std. Error**	**Wald Chi-Square**	**df**	**Sig.**	
Cell Phone Use (C)			7.156	2	0.028	
Hands-free (HF)	-0.490	0.1832	7.148	1	0.008	
Hand-held (HH)	-0.325	0.1845	3.102	1	0.078	
Driver's gender (G)			3.608	1	0.057	
Male	-0.281	0.1479	3.608	1	0.057	
Initial Speed (V_{FS})	-0.206	0.0445	21.413	1	0.000	
Initial Headway Distance (D_s)	0.013	0.0042	9.472	1	0.002	**0.622**
C *D_s			10.773	2	0.005	
HF*D_s	0.015	0.0045	10.580	1	0.001	
HH*D_s	0.012	0.0044	7.263	1	0.007	
G*D_s			11.539	1	0.001	
Male*D_s	0.011	0.0033	11.539	1	0.001	
(Intercept)	3.020	0.4978	36.810	1	0.000	

Table 2: Generalized linear model results of the deceleration adjusting time

Parameter	**Driving Behavior Parameters**					**R^2**
	B	**Std. Error**	**Wald Chi-Square**	**df**	**Sig.**	
Brake Reaction Time (BRT)	.132	.1050	1.587	1	.208	
TTC	.041	.0278	2.179	1	.140	**0.459**
BRT*TTC	-.021	.0102	4.139	1	.042	
(Intercept)	.967	.1697	32.484	1	.000	
Parameter	**Considering Influencing Factors**					**R^2**
	B	**Std. Error**	**Wald Chi-Square**	**df**	**Sig.**	
Cell Phone Use (C)			1.498	2	0.473	
Hands-free (HF)	-0.310	0.3195	0.939	1	0.333	
Hand-held (HH)	-0.101	0.3205	0.100	1	0.752	
Driver's gender (G)			3.736	1	0.053	
Male	-0.426	0.2205	3.736	1	0.053	
Brake Reaction Time (BRT)	-0.565	0.1752	10.398	1	0.001	
TTC	0.195	0.0504	14.973	1	0.000	
C *BRT			15.689	2	0.000	
HF*BRT	0.760	0.1923	15.611	1	0.000	
HH*BRT	0.463	0.1674	7.662	1	0.006	**0.534**
C *TTC			6.727	2	0.035	
HF*TTC	-0.128	0.0507	6.336	1	0.012	
HH*TTC	-0.118	0.0578	4.136	1	0.042	
G*BRT			20.245	1	0.000	
Male*BRT	0.579	0.1287	20.245	1	0.000	
G*TTC			4.966	1	0.026	
Male*TTC	-0.093	0.0416	4.966	1	0.026	
BRT*TTC	-0.044	0.0128	12.054	1	0.001	
(Intercept)	1.315	0.2881	20.846	1	0.000	

Table 3: Generalized linear model results of the maximum deceleration rate

Parameter	Driving Behavior Parameters					R^2
	B	**Std. Error**	**Wald Chi-Square**	**df**	**Sig.**	
Brake Reaction Time (BRT)	2.253	.2999	56.424	1	.000	**0.578**
TTC	.668	.0794	70.706	1	.000	
BRT*TTC	-.158	.0291	29.657	1	.000	
(Intercept)	-10.501	.4848	469.132	1	.000	
Parameter	**Considering Influencing Factors**					**R^2**
	B	**Std. Error**	**Wald Chi-Square**	**df**	**Sig.**	
Cell Phone Use (C)			6.012	2	0.049	**0.717**
Hands-free (HF)	1.718	0.8573	4.018	1	0.045	
Hand-held (HH)	0.636	0.8625	0.544	1	0.461	
Driver’s gender (G)			13.946	1	0.000	
Male	1.755	0.4700	13.946	1	0.000	
Brake Reaction Time (BRT)	3.982	0.4497	78.413	1	0.000	
TTC	0.726	0.1148	40.015	1	0.000	
C *BRT			20.082	2	0.000	
HF*BRT	-0.921	0.5129	3.224	1	0.073	
HH*BRT	-1.830	0.4495	16.577	1	0.000	
C *TTC			15.195	2	0.001	
HF*TTC	-0.155	0.1291	1.438	1	0.230	
HH*TTC	0.344	0.1543	4.958	1	0.026	
G*BRT			4.857	1	0.028	
Male*BRT	-0.737	0.3346	4.857	1	0.028	
BRT*TTC	-0.158	0.0333	22.413	1	0.000	
(Intercept)	-13.147	0.7561	302.317	1	0.000	

Table 4: Comparison of the minimum headway distance from experiment data and simulation results

		Minimum Headway Distance (m)		Relative Absolute Error (m)
		Experiment Data	Model Results	
No Phone	Female	15.16	15.26	3.23
	Male	12.38	11.77	3.59
Hands-free	Female	16.55	16.56	2.73
	Male	12.59	12.01	4.89
Hand-held	Female	18.31	17.98	2.77
	Male	14.05	13.82	4.03
Total		14.81	14.52	3.55

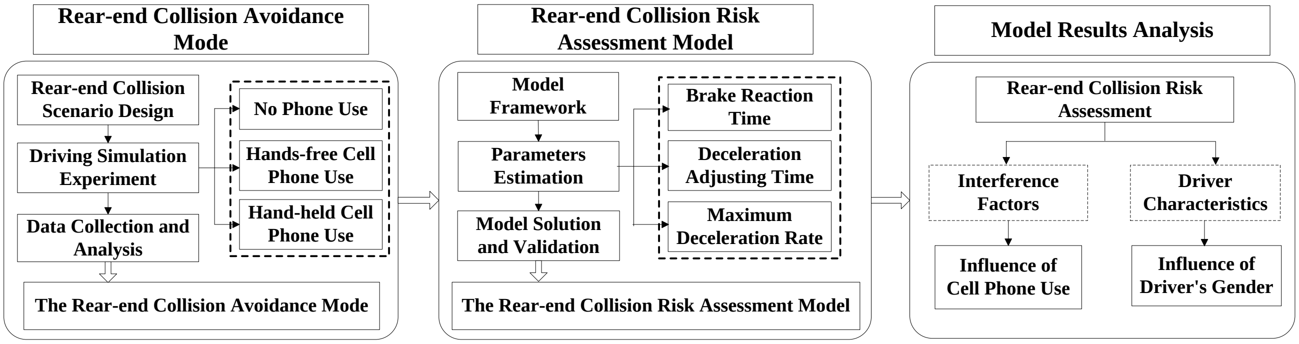
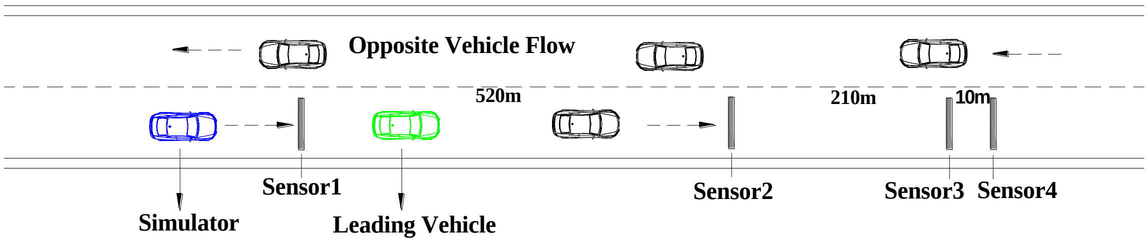


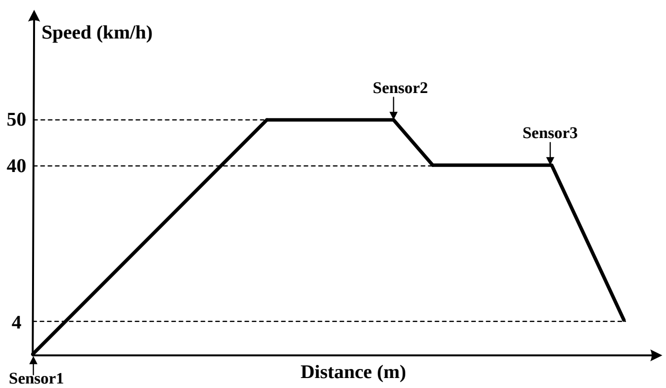
Figure 1: Research framework

Figure 2: The BJTU driving simulator



a. The test road segments

b. The car-following scenario



c. The speed profile of leading vehicle

Figure 3: The experiment scenario

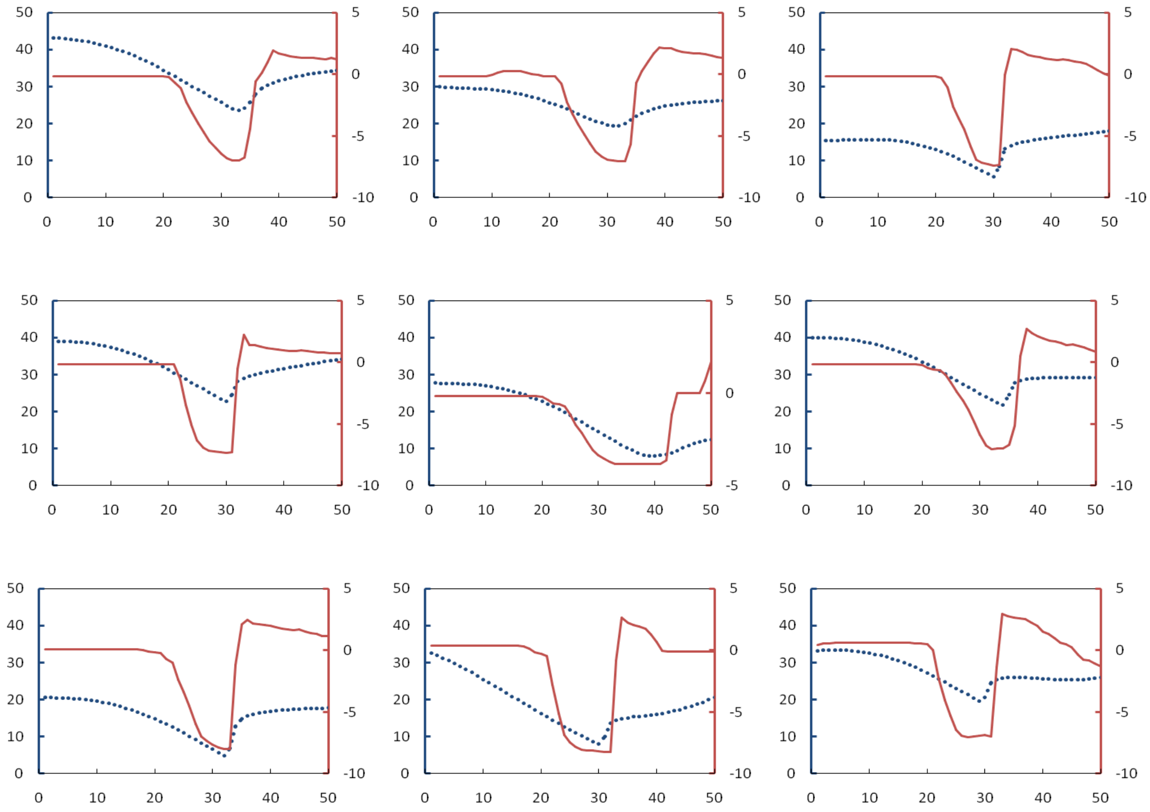


Figure 4: Drivers' acceleration rate and headway distance changes in the collision avoidance process (the red solid line represents drivers' acceleration rate and the blue dot line represents the headway distance between the simulator and the leading vehicle)

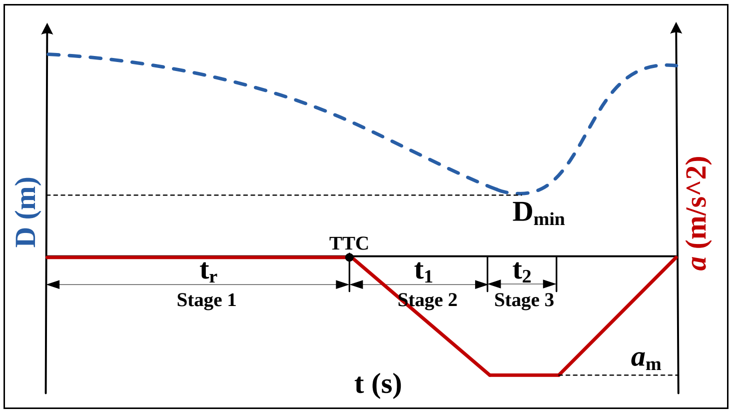


Figure 5: The rear-end collision avoidance mode

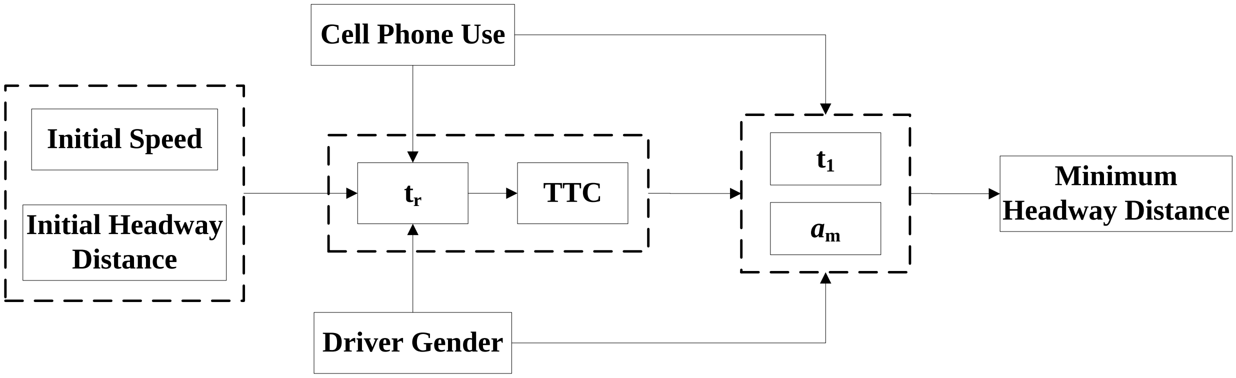
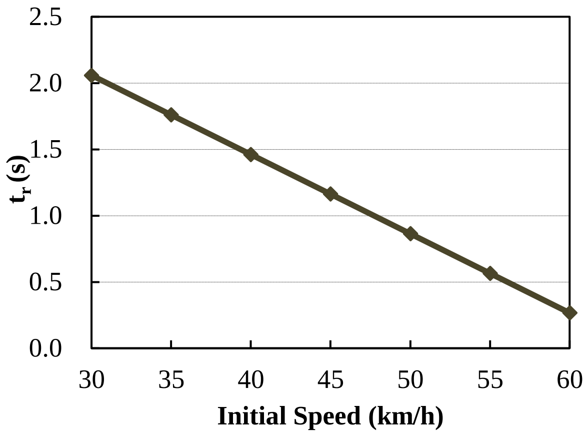
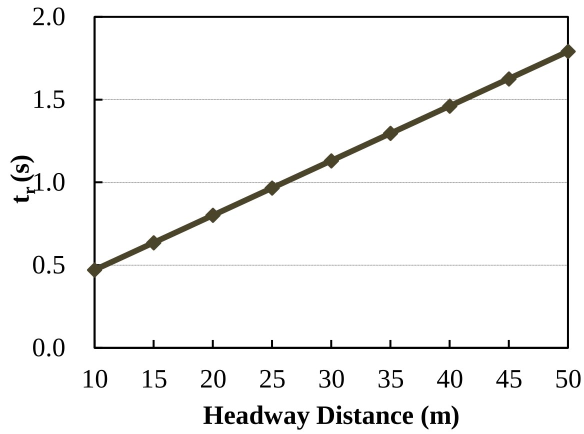


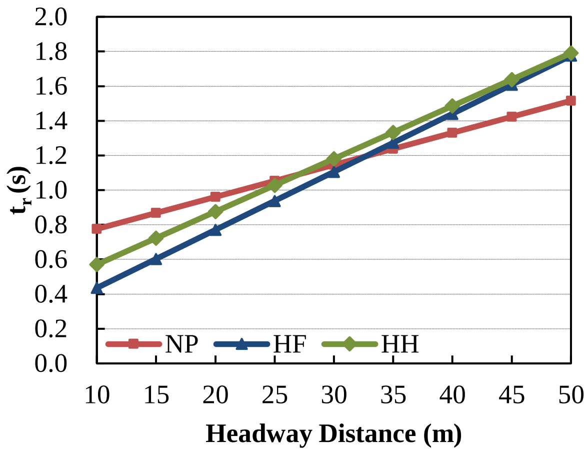
Figure 6: Inter-relation of key variables in the rear-end collision avoidance process



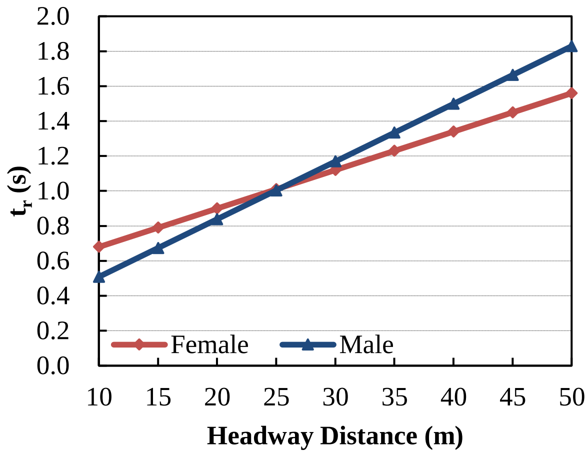
a. D_s = 40 m



b. V_{FS} = 40 km/h

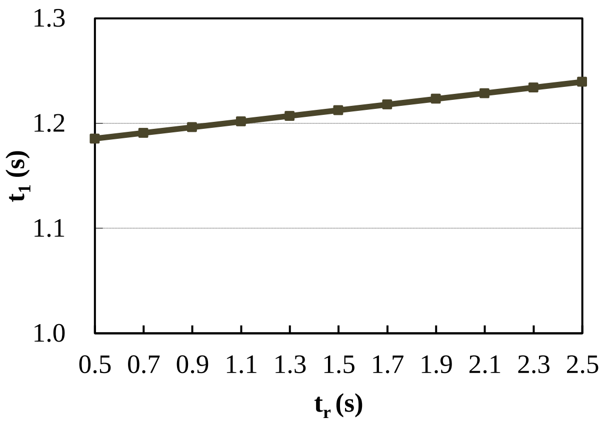


c. V_{FS} = 40 km/h

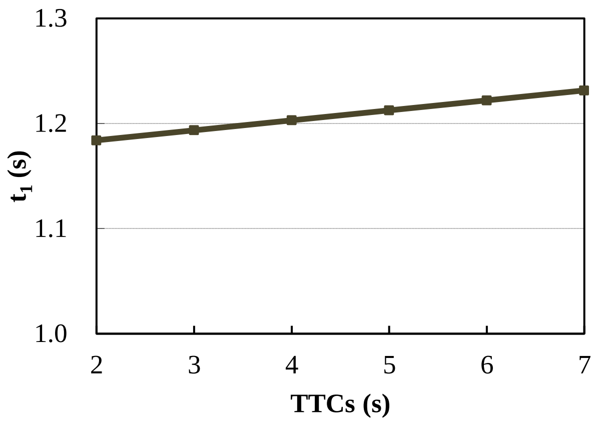


d. V_{FS} = 40 km/h

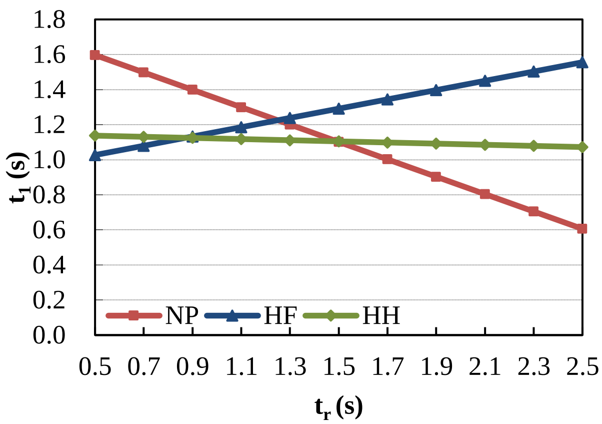
Figure 7: Relationship between driver's brake reaction time and the significant factors



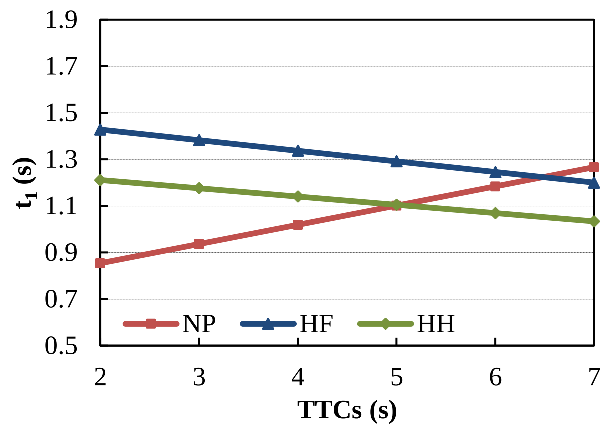
a. TTC = 5 s



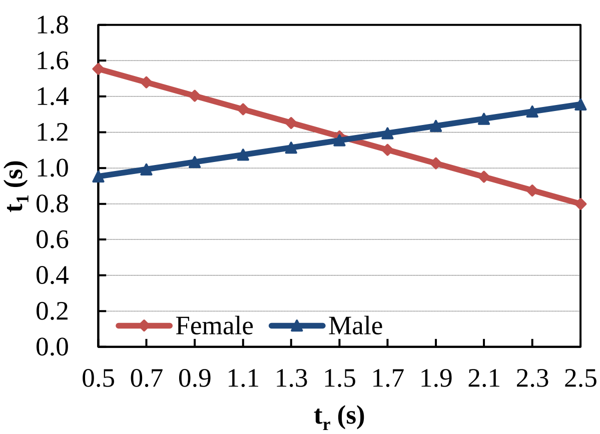
b. t_r =1.5 s



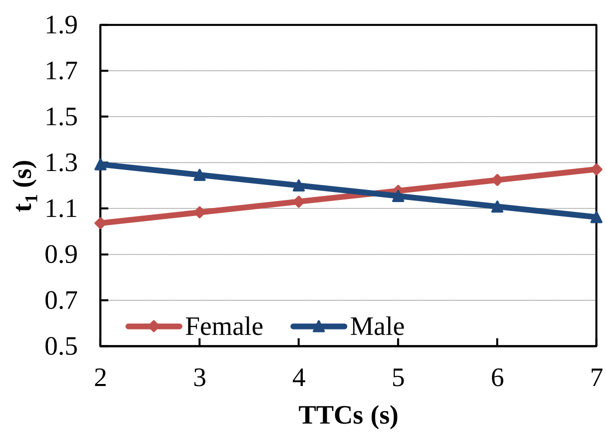
c. TTC = 5 s



d. t_r =1.5 s

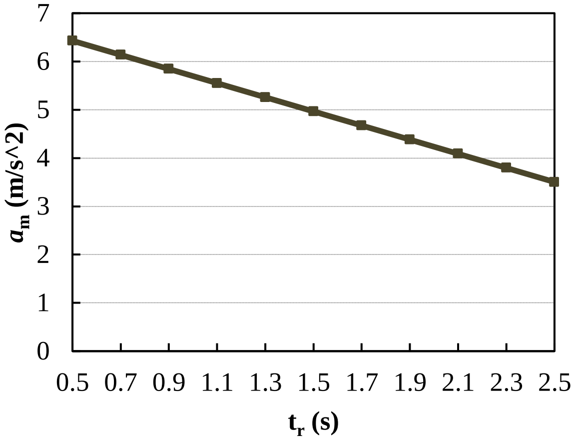


e. TTC = 5 s

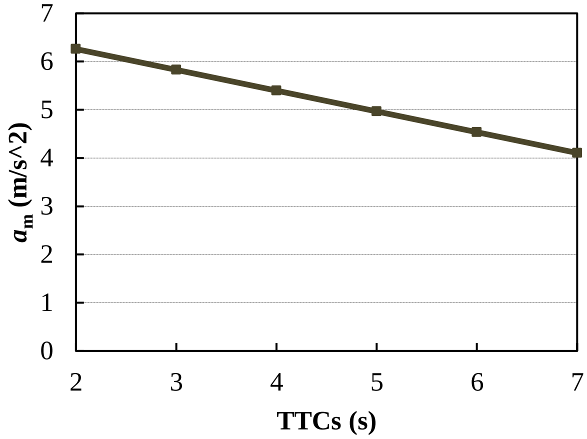


f. t_r =1.5 s

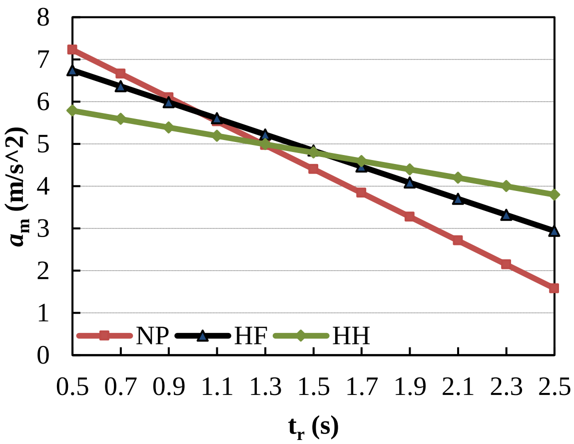
Figure 8: Relationship between driver's deceleration adjusting time and the significant factors



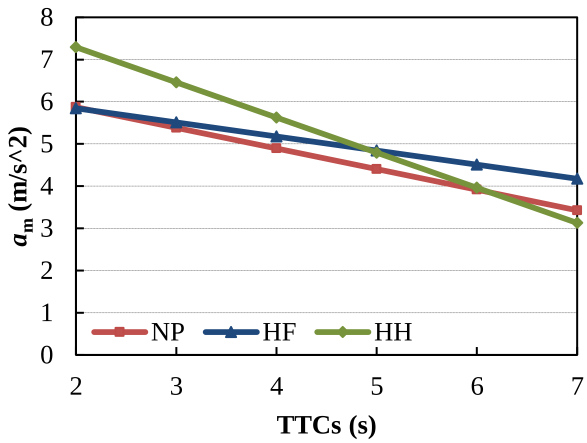
a. TTC = 5 s



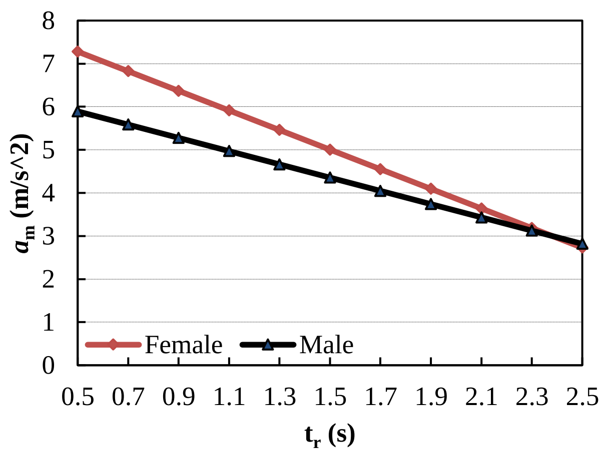
b. t_r =1.5 s



c. TTC = 5 s



d. t_r =1.5 s



e. TTC = 5 s

Figure 9: Relationship between driver's maximum deceleration rate and the significant factors

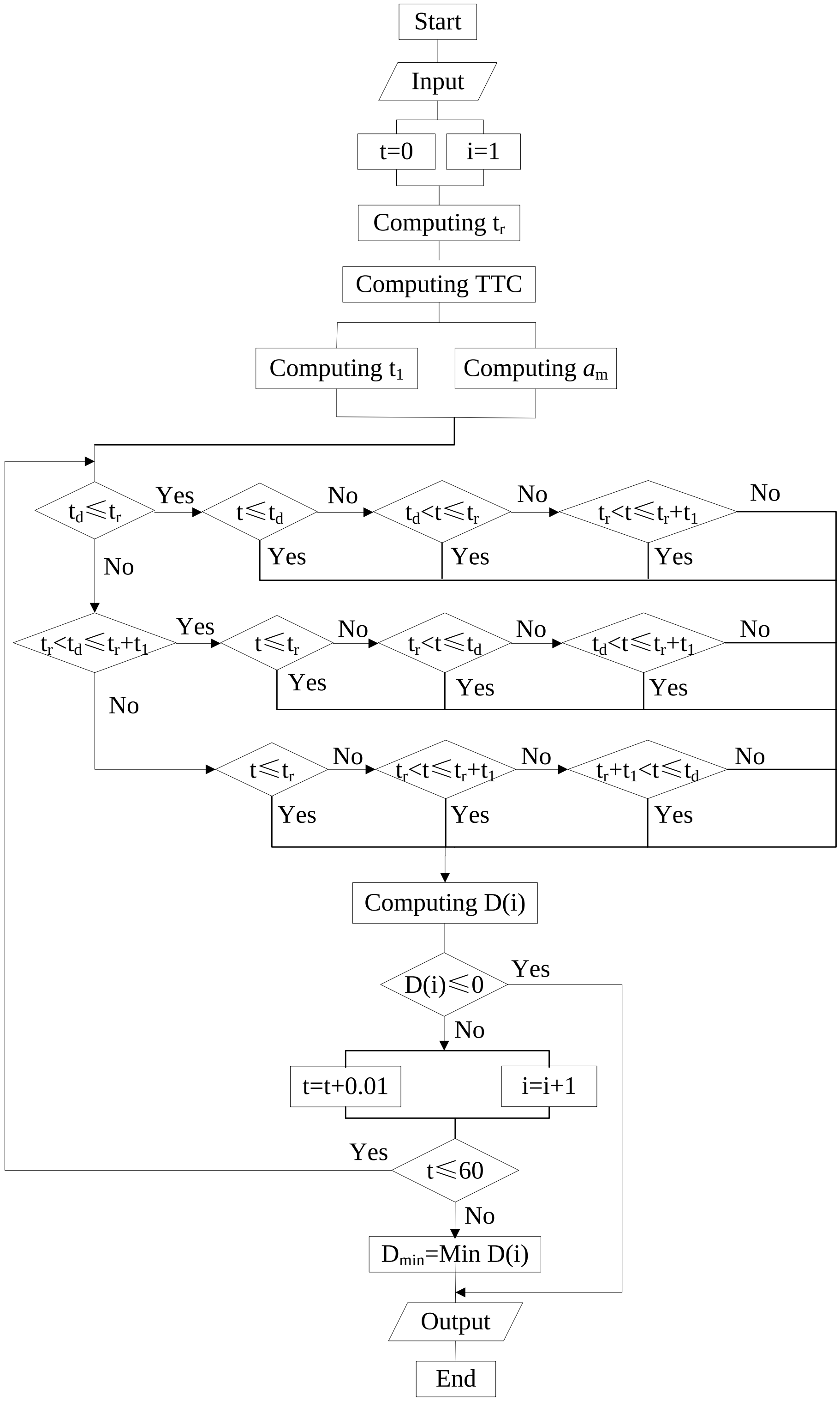


Figure 10: The flow diagram of the model algorithm

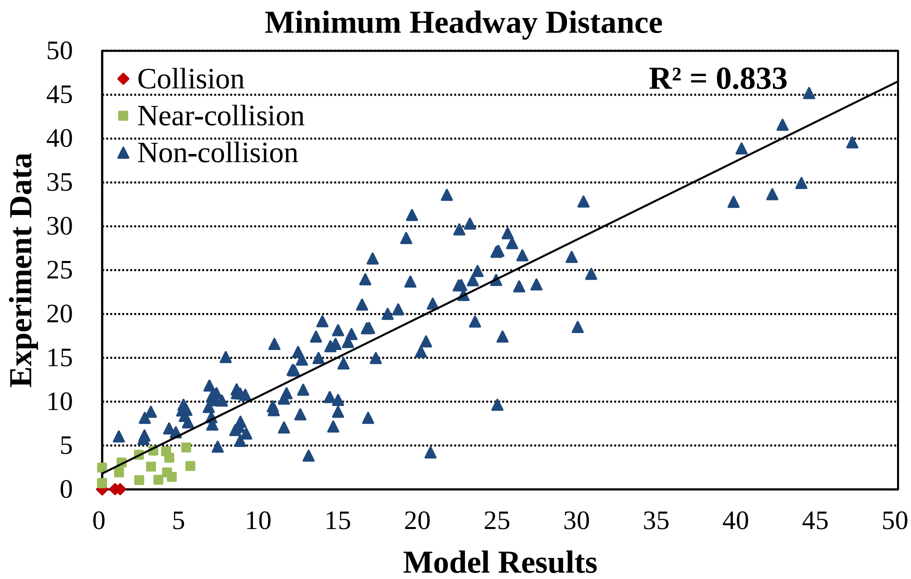
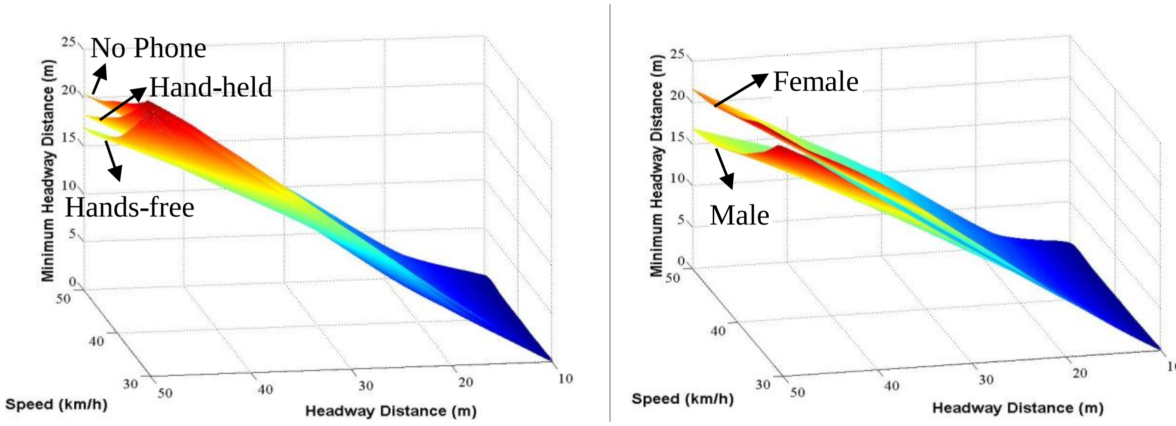


Figure 11: The relationship between the experiment data and the prediction results



a. Differences between different cell phone use conditions for male drivers

b. Differences between different driver gender in hands-free condition

Figure 12: Relationship of the minimum headway distance, the initial speed, and the initial headway distance