World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:3, No:9, 2009

Modeling Reaction Time in Car-Following Behaviour Based on Human Factors

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Open Science Index, Civil and Environmental Engineering Vol:3, No:9, 2009 publications.waset.org/2937/pdf

***Abstract*—**This paper develops driver reaction-time models for car-following analysis based on human factors. The reaction time was classified as brake-reaction time (BRT) and acceleration/deceleration reaction time (ADRT). The BRT occurs when the lead vehicle is barking and its brake light is on, while the ADRT occurs when the driver reacts to adjust his/her speed using the gas pedal only. The study evaluates the effect of driver characteristics and traffic kinematic conditions on the driver reaction time in a car-following environment. The kinematic conditions introduced urgency and expectancy based on the braking behaviour of the lead vehicle at different speeds and spacing. The kinematic conditions were used for evaluating the BRT and are classified as normal, surprised, and stationary. Data were collected on a driving simulator integrated into a real car and included the BRT and ADRT (as dependent variables) and driver's age, gender, driving experience, driving intensity (driving hours per week), vehicle speed, and spacing (as independent variables). The results showed that there was a significant difference in the BRT at normal, surprised, and stationary scenarios and supported the hypothesis that both urgency and expectancy had significant effects on BRT. Driver's age, gender, speed, and spacing were found to be significant variables for the BRT in all scenarios. The results also showed that driver's age and gender were significant variables for the ADRT. The research presented in this paper is part of a larger project to develop a driver-sensitive in-vehicle rear-end collision warning system.

***Keywords*—**Brake reaction time, car-following, human factors, modeling.

I. INTRODUCTION

REAR-END collisions are one of the most common types of collisions. In 2007, over 1.819 million rear-end collisions occurred and accounted for 30.2 percent of all reported collisions in the US [1]. Rear-end collisions occurred in car-following situations. Typically, driver, vehicle, roadway, and environment characteristics influence collision occurrence and injury severity. Driver characteristics (or human factors) include age, gender, driving experience, and mental/physical health. Research has shown that two principal factors involved in the majority of rear-end collisions are driver's inability to perceive and/or react to a lead vehicle's actions and following a lead vehicle too closely [2]. Studies have revealed that driver perception and reaction to the lead vehicle's action is the prime contributing factor in rear-end collisions [3]. Environmental factors such as ice and poor road surface contribute to relatively few rear-end collisions since they predominately occur during daylight hours, on straight roads, and under clear weather conditions [4].

Car-following behaviour is an essential component of rear-end collision avoidance algorithms and microscopic traffic simulation models. The most important parameter used in the calibration of car-following models is driver's brake-reaction time (BRT) which has been examined in a number of studies. The brake-reaction time in response to braking of the lead car definitively differs from the reaction to an obstacle on the road or from the reaction to a crossing vehicle at an intersection [5]. In psychological studies, the driver reaction process is further represented in three states: mental processing, movement, and device response. Driver reaction time is defined in earlier car-following research as the sum of the perception time and the foot movement time [6]. The reaction time depends on the driving task and individual driver characteristics [7]. The driving tasks include car-following, lane-change, left-turn, and right-turn tasks.

The reaction time during the car-following task is the time lag that the follower uses to react to the change in the leader's driving behaviour. The driver reaction time in a car-following scenario can also be defined as the reaction time during the acceleration and deceleration manoeuvres. In the case of acceleration/deceleration manoeuvres, the car-following driver will accelerate or decelerate to sustain the desired speed for the given kinematic conditions. The desired speed is defined as the maximum speed at which the following driver would travel based on the given kinematic conditions. This speed can also be influenced by the speed limit and other factors such as weather conditions and visibility. The car-following driver reacts to adjust his/her speed by using the gas pedal only or by using the brake pedal in the case the lead vehicle is braking and its brake light is on. The term acceleration or deceleration reaction time (ADRT) is used when the driver reacts to adjust his/her speed by only using the gas pedal,

In our study, the ADRT is defined as the time difference between the moment the driver receives the visual signal to adjust his/her speed and the moment he/she starts to adjust the gas input. The term brake-reaction time (BRT) is used when the driver reacts to brake in response to the lead vehicle

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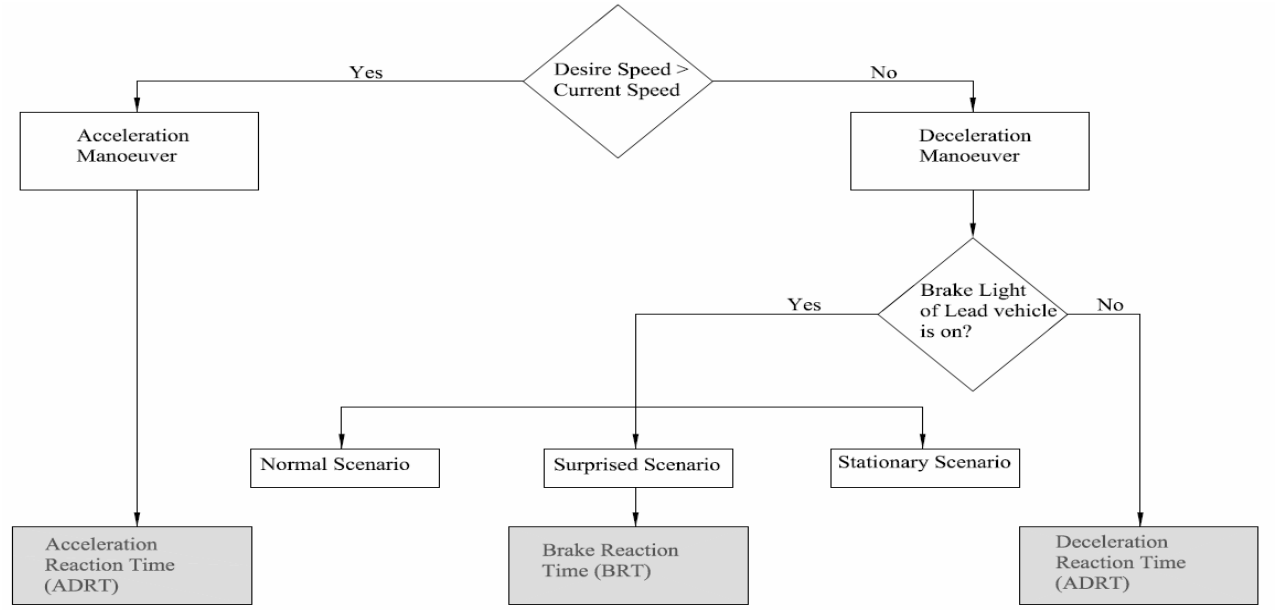


Fig. 1 Logic of car-following maneuvers and reaction times

braking. BRT is defined as the time difference between the moment the driver receives the lead vehicle brake light signal and the moment he/she touches the brake pedal. The following driver can also face a forward collision situation because of a surprised behaviour of the lead vehicle such as when it applies emergency braking or stops at short distance headway. Figure 1 illustrates the car-following logic that includes the different maneuvers and the respective reaction times. As noted, the BRT and ADRT are essential components of this logic.

Various Organizations have established some standards for BRT such as 2.5 s in the United States and 2 s in Europe, but these values have been criticized by many researchers [8]. The author also stated that several studies have recommended BRT values that differ by a factor of almost 4.

The variation of the results is due to the use of different signals, responses, and testing situations Therefore, the use of these values for modeling car-following behaviour is questionable. Previous studies have focused only on specific factors, but a reaction time study should examine all the factors including driver specific and situational factors. However, placing drivers in surprised (emergency) or even urgent situations and measuring the perception and movement times is not easy in real road experiments. It is also very challenging to design a scenario that can account for all the factors at the same time.

This paper overcomes these challenges by modeling such car-following scenarios based on data obtained from a driving simulator. The objective of the study is to determine typical reaction times under car-following environment for different driving conditions and driver characteristics. The main tasks of the study, which is part of a larger project to develop a driver-sensitive in-vehicle rear-end collision warning system, are: (1) to conduct a comprehensive literature review on reaction time, (2) to design car-following scenarios for different driving conditions at different speeds and spacing, (3) to conduct driving simulator experiments, and (4) to analyze the variables to gain some insight into their effects on the driver reaction time, and (5) to develop analytical models for BRT and ADRT. Before describing these tasks, it is useful to present first the mathematical car-following model.

II. MATHEMATICAL CAR-FOLLOWING MODEL

Various theories have been developed to express the traffic flow process. These theories model the driver behavior in different traffic flow situations. The most common class of such theories attempts to describe the car-following behavior. The car-following theories are based on the follow-the-leader concept, where the rules of how a driver follows the immediate leading vehicle are established based on both experimental observations and theoretical considerations. The background of such theories can be found in detail in Brackstone and McDonald [9] and elsewhere in the literature.

Based on these theories, researchers have developed many car-following models that represent the driver's car-following behavior. These models predict the speed or the acceleration or deceleration rate of the following vehicle at each time step during a continuous traffic flow. Mehmood el al. [10] used an action point model to calibrate and validate the car-following behaviour based on the follow-the-leader concept. Information of the second lead vehicle was also considered in modeling the car-following behaviour. The simplified formulation of their model is given by:

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$$a^F(t) = \left[\frac{VD^F(t) - V^F(t)}{T^F(t)} \right] \times 0.278 \quad (1)$$

where, $a^F(t)$ = acceleration/deceleration rate of the following vehicle at time t (m/s^2), $VD^F(t)$ = desired speed of the following vehicle at time t in both steady and non-steady state conditions (km/h), $V^F(t)$ = current speed of the following vehicle at time t (km/h), $T^F(t)$ = reaction time of the following vehicle driver at time t (s), and 0.278 = unit conversion factor, for converting speed from km/h to m/s.

The following vehicle drivers drive in three regimes: coasting, accelerating, and decelerating. The following drivers respond to the lead vehicle's deceleration and acceleration maneuvers. It is assumed that the decelerating regime is divided into two scenarios: when the brake light of the lead vehicle is on the following vehicle driver will apply brakes otherwise he/she will adjust the speed using only the gas pedal by decreasing the gas or throttle input. It is also assumed that while coasting if the following vehicle driver wishes to accelerate (the accelerating regime) he/she will increase the speed by increasing the gas or throttle input.

In this study, the following vehicle driver's reaction time is modeled during the accelerating and accelerating regimes. As previously mentioned, the reaction time $T^F(t)$ was further classified as the reaction time for the accelerating or decelerating regime using only the gas pedal (ADRT) and the reaction time for the decelerating regime using the brake pedal (BRT). Substituting these reaction times into Eq. (1), then

$$a^F(t) = \left[\frac{VD^F(t) - V^F(t)}{ADRT(t)} \right] \times 0.278 \quad (2)$$

$$a^{Fd}(t) = \left[\frac{VD^F(t) - V^F(t)}{BRT(t)} \right] \times 0.278 \quad (3)$$

where, $a^F(t)$ = acceleration/deceleration rate of the following vehicle at time t in the accelerating or decelerating regimes using only the gas pedal (m/s^2), $a^{Fd}(t)$ = deceleration rate of the following vehicle at time t using only the brake pedal (m/s^2), ADRT(t) = reaction time of the following vehicle driver at time t in the accelerating or decelerating regimes using only the gas pedal (s), BRT(t) = reaction time of the following vehicle driver at time t in the decelerating regime using only the brake pedal (s). General forms of Eqs. (2) and (3) will be developed as part of this project.

III. DRIVER AND SITUATIONAL FACTORS

Researchers have identified many factors that influence driver brake reaction time and divided them into driver factors and situational factors. The driver factors include driver age, gender, and experience. The situational factors depend on the driving tasks which include expectation, urgency, and cognitive load.

A. Driver Factors

Generally, it appears that age slows the driver brake reaction time. Surprisingly, several studies have produced mixed results. Broen and Chiang [11] found that older drivers react slowly in some cases. But Lerner [12] found no effect of age on reaction time. Green [8] identified several reasons for the mixed results: biased sample, old people with better health drive like young people, and experience and more practice which compensate for the slowing of perception or movement time. The perception of urgency may also compensate for the age factor. Young drivers may warrant a low urgency compared to old drivers while facing the same dangerous situation. Aging produces vision loss that results in a slower braking response, particularly at night and in poor weather conditions. Summala and Koivisto [13] found that older drivers compensate for their poorer braking by driving slower.

Like age, the research findings on the effect of gender are also mixed. Some researchers have found faster reaction time for men [14] and others found no difference [15]. Driving experience has not been explicitly addressed as a variable in the literature. Summala et al. [16] measured driving experience by the lifetime mileage driven. The study found no effect of driving experience on the perception of the lead vehicle's braking onset while performing the in-vehicle tasks.

B. Situational Factors

Expectancy. The terms 'expected' and 'unexpected' are used in the literature to refer, respectively to drivers alerted and expecting a signal to brake and those that use unexpected signal. Some researchers have used the term expected when drivers are explicitly told that a brake response must be made at a particular stimulus. In a car-following scenario, drivers always expect the normal deceleration rate except when a lead vehicle behaves unexpectedly, such as suddenly braking with a maximum deceleration rate to avoid an unexpected situation ahead. This is also referred to as the expectancy of the car-following driver. The results of the expected reaction time vary significantly in the literature. Some studies reported an expected reaction time in the range of 1.3 to 1.4 s [17]. Other studies reported a range from 1.14 to 1.21 s [18]. The third cluster of studies agrees with a value of 0.9 s [19]. The wide variation in these results is due to the use of different signals and situations for determining the driver reaction time.

Urgency. Urgency is usually defined by the time-to-collision (TTC), where shorter TTC is more urgent and vice versa. The TTC depends on vehicle speed and spacing (distance headway) and can be manipulated by varying the distance, speed, or both. Chang et al. [20] found that a half second reduction in the reaction time to a yellow light as speed increased from 25 to 40 mph, but found no further reduction for speeds up to 55 mph. Schweitzer et al. [21] studied the effect of both speed and the following distance on the reaction time and found no effect of speed on the reaction time. However, the authors did no account for the behaviour of the lead vehicle (i.e. expectancy). Other studies used surprised intrusion paradigms (e.g. intrusion of a policeman)

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to determine the effect of the TTC on the reaction time. Both studies found totally different results. Summala and Koivisto [13] concluded that reaction time decreased by almost 1 s as the TTC decreased from 6 s to zero, while Hankey [15] found that the reaction time increased by 0.4 s as the TTC grew shorter from 4.35 to 2.85 s. Green [8] stated that these opposing conclusions are likely due to methodological differences. Some studies also found that at very short TTC drivers prefer the steering maneuver rather than braking [22]. Urgency in a car-following scenario cannot be defined by the TTC alone. The behaviour of the lead vehicle is very important, such as braking then accelerating, continuously decelerating, or even becoming stationary.

Cognitive Load. Several researchers found that high cognitive load slows the driver reaction time [8]. Two primary sources of cognitive load are the use of in-vehicle devices and complicated drivers path such as successive turns in a winding road. Korteling [23] and Summala et al. [16] found slower reaction time when the road has more turns and the drivers viewed in-car displays, respectively. The use of cellular phones also increases the cognitive load. Several studies attempted to determine the effect of cellular phone use on the reaction time. The results showed that cellular phones increased the reaction time by about 0.5 s [24]. It is very difficult to calibrate the effect of cognitive load on reaction time since precise tracking of driver's in-vehicle activities is not possible. For these reasons, the cognitive load is not considered in this study.

IV. EXPERIMENTAL PROGRAM

A. Participants and Apparatus

Sixty subjects participated in the experiment (32 males and 28 females), aged 18-70 years. To account for the variability among the driver population, the distribution of age and gender in the selected sample of the tested drivers was selected to be the same distribution of the driver population in Canada [25]. The drivers were distributed in three age groups, 18-24, 25-54, and 55+ years, where the number of drivers was 8, 35, and 17, respectively. The sample breakdown is given in table 1.

TABLE I
SAMPLE BREAKDOWN OF PARTICIPANTS

Gender	Age group and number of drivers					
	18-24 years		25-54 years		55+ years	
	Number	%	Number	%	Number	%
Female	4	12.8	17	59.9	8	27.3
Male	4	13.0	18	57.9	9	29.1

The participants were tested using STISIM: a high fidelity, interactive driving simulator that offered a 45-degree horizontal field of view and integrated in a real car equipped with steering, brake, accelerator, and automatic transmission control. The display system used Epson EMP-S3 LCD projector that focused the moving images on a projection screen. The participants sat in the car which was located in front of the projection screen. The vehicle speed (km/h) was displayed on the front screen. Before the start of the experiment, each participant was given instructions regarding the experiment.

B. Brake Reaction-Time Data

To replicate the driver behaviour in the car-following scenario, three driving conditions were tested at different spacing and driving speeds. These conditions are categorized as normal, surprised, and stationary based on the driving behaviour of the lead vehicle, also called principle other vehicle (POV), The following vehicle is also referred to as the subject vehicle (SV). The maximum comfortable deceleration rate an individual driver is willing to use in non-emergency situations (normal driving) ranges from 2 to 3.45 m/s^2 [26]. However, in an emergency situation, drivers are expected to brake at a deceleration rate ranging from 5 to 8.5 m/s^2 [27]. The higher deceleration rate of 8.5 m/s^2 was reported for the new light vehicles. The braking capability of the vehicle decreases with wear and tear. In this study, two deceleration rates of the lead vehicle were selected for normal and surprised situations, as described later. Before the actual experiments, all participants drove a few practice experiments to familiarize themselves with the driving simulator. The simulation runs for normal, surprised, and stationary conditions were chosen at random for each participant. Figure 2 shows the geometry and variables used in the car-following logic.

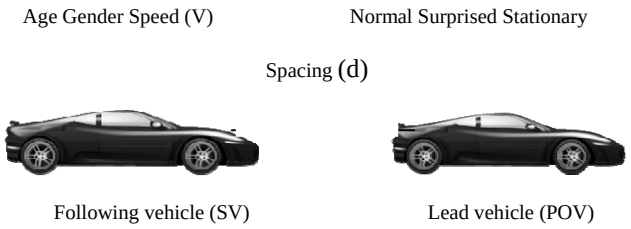


Fig. 2 Car-following vehicle dynamics

In all three scenarios, the SV begins to accelerate from the stopped position to the target speed of 60, 80, or 100 km/h. For each run, the drivers are directed to accelerate at the test speed and maintain their speeds until they react in response to the action of the lead vehicle. The SV driver is directed to maintain his/her speed throughout the experiment. At a distance of 1.1 km down the road, the POV appears in the same lane at a certain spacing and speed depending on the type of scenario. In the normal scenario, the POV appears at a spacing of 20, 30, or 40 m and travels at the same speed as the

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SV. At a distance of 1.2 km the POV decelerates and its brake lights are turned on. The SV driver reacts in response to the braking of the POV. The POV decelerates for a moment and then starts to travel at the same speed. The average deceleration rate of the POV ranged from 2.5 to 3.5 m/s^2. This scenario is designed to mimic a normal car-following behaviour at different driving speeds and spacing. The normal car-following behaviour is less likely to contribute to a rear-end collision.

In the surprised scenario, the POV appears at a spacing of 10, 20, or 30m and travels at the same speed as that of SV. These spacing combinations for the surprised scenario were used since the drivers have difficulty in judging the surprised braking rate at larger spacing. At a distance of 1.2 km the POV decelerates at a very high rate and then stops. This is a surprised driving condition compared to a normal driving behaviour. The average deceleration rate of the POV ranged from 4 to 7.5 m/s^2. The SV driver reacts by stopping the vehicle to avoid a rear-end collision. In the stationary scenario, the POV is in the stationary condition at different distances from the SV. The POV appears (as stationary vehicle) at a distance of 20, 30, or 40m. The SV driver brakes to avoid colliding with the stationary vehicle. This scenario also creates a rear-end collision situation at different speeds and spacing. The independent variables included urgency, expectancy, age, gender, and driving experience. Urgency is addressed by varying the speeds of the lead and following vehicles and the spacing between them. The expectancy is addressed by varying the lead vehicle braking behaviour at different traffic kinematic conditions.

C. Acceleration/Deceleration Reaction-Time Data

The urgency and expectancy cannot be used to model the ADRT when the driver wishes to accelerate or decelerate to sustain his/her desired speed. Therefore, the reaction time was initially collected during the start of the experiment when the driver would accelerate, and represented the acceleration-reaction time. The participants were instructed to start the vehicle as soon as they see the start screen. The reaction time data were collected from the onset of the start of the experiment to the time when the driver presses the gas pedal to start the vehicle. When the driver wants to accelerate while driving on a specific speed he/she will only use the gas pedal. There were 27 runs for each participant for the collection of the BRT data at different speeds, spacing, and situations. In this initial experiment, although the drivers were instructed to start the vehicle immediately when they see the start screen, some drivers had reacted too slowly and some were very fast during the start of the experiment, producing some bias into the data. In addition, the experiment did not provide data related to the deceleration reaction time which the experiment indicated that it might be different from the acceleration reaction time.

Therefore, another experiment was designed to omit the outliers and check the difference between the reaction times during the acceleration and deceleration tasks, where in the deceleration task the drivers use only the gas pedal. A visual signal was used to instruct the participants that they need to accelerate or decelerate while driving at a specific speed. The speed limit signs were used as a visual signal. These signs appeared at a distance of 40 m from the subject vehicle. Several experiments were run and it was observed that the drivers of each age group can easily read the speed limit signs at a distance of 40 m. The participants were instructed to start the vehicle as soon as they see the start screen and to accelerate or decelerate at each speed limit sign to follow the displayed speed. The reaction time data were collected from the onset of visual signal to when driver uses his/her gas pedal to adjust his/her speed. Three readings were collected one at the start and two at the speed limit signs. The ADRT data collected in this case were used to omit the outliers of the acceleration-reaction time data collected during the start of the experiments. Twenty five subjects participated in the additional experiments (16 males and 9 females), aged 18-70 years.

V. DATA ANALYSIS

A. Brake Reaction-Time

As described previously, the type of scenario (normal, surprised, and stationary) and the speed-distance combinations within each scenario introduce expectancy and urgency. The mean BRT for each scenario for each speed-distance combination is shown in figure 3.

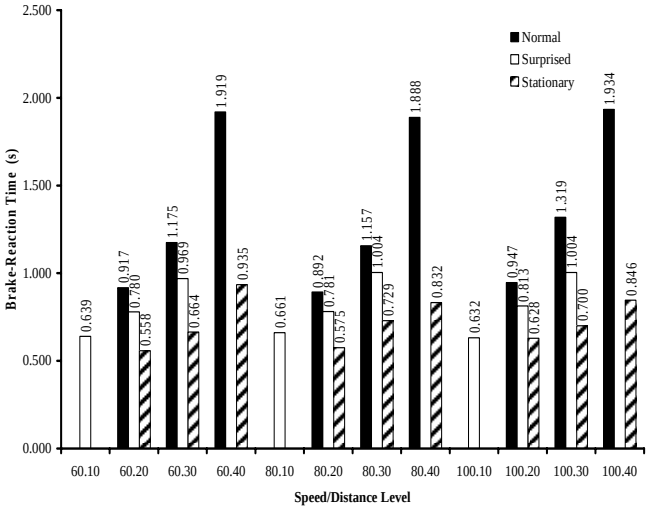


Fig. 3 Brake-reaction time for different speed/distance levels for each scenario

As noted, there is a clear effect of the expectancy and urgency on the brake-reaction time. As expected, the BRT decreased with the increase in the level of urgency behaviour of the lead vehicle (normal vs. surprised). The drivers react slowly for normal deceleration compared to the stationary and surprised conditions of the lead vehicle. The drivers also react slowly at larger spacing during the course of each scenario. In other words, the BRT is directly proportional to the available

time to collision at the braking onset of the lead vehicle. But the BRT also varies for different types of scenarios (normal, surprised, and stationary) at the same spacing and speed. Therefore, the results indicate that the level of expectancy and urgency has a significant effect on the brake-reaction time in a car-following scenario.

The brake-reaction time as a function of gender, age, driving experience, and driving intensity (driving hours per week) for each type of car-following scenario was analyzed. As an example, the variation of the BRT with gender is shown in figure 4.

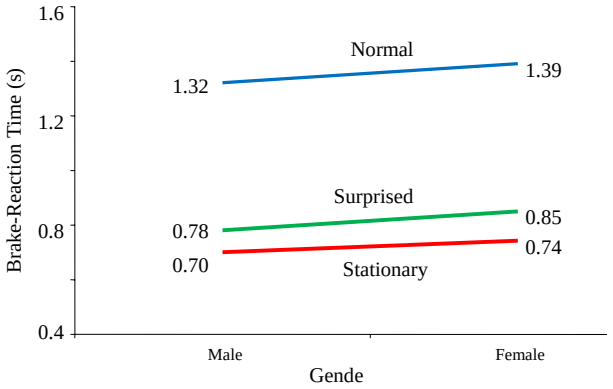


Fig. 4 Comparison of brake-reaction time based on gender

The BRT of females was larger than that of males in all scenarios. The BRT also increased for all age groups at normal, surprised, and stationary scenarios. However, there is a slight difference in the BRT for all age groups in all types of scenarios, except the normal scenario in which the middle and old age groups were found to be 0.12 s slower than the young age group. The driving experience and driving intensity have mixed effects on the brake-reaction time. The brake-reaction time of the fairly experienced drivers is higher than that of the beginners and well experienced drivers in the normal and stationary scenarios, but smaller in the surprised scenario. The driving experience and driving intensity vary for drivers of different age groups and gender.

The difference between the BRT of stationary and surprised scenarios is smaller compared to that between the normal and the other two type of scenarios (surprised and stationary). The stationary scenario also acts like a surprised scenario since the stopping distance ranged from 20 to 40 m which is a surprised situation especially at higher speeds. However, the stationary scenario introduces more urgency since the lead vehicle is not moving. As expected, the BRT decreased markedly with the unexpected deceleration rates of the lead vehicle for all variables. In other words, for the normal scenario in which the average deceleration rate of the lead vehicle is of a normal driving situation, drivers react slowly compared to the stationary and surprised scenarios, as expected.

B. Acceleration/Deceleration Reaction Time

As previously mentioned, the acceleration-reaction time data were collected at the start of each simulation run of the BRT experiment and there were 27 simulation runs for each participant. The average of these runs was considered as the acceleration reaction time. The outliers in the first experiment were omitted and the resulted acceleration-reaction time data were analyzed. Based on the data of the second improved experiment, the ranges of the acceleration-reaction time for the young, middle, and old age groups were 0.4-1.1 s, 0.6-1.3 s, and 0.6-1.5 s, respectively. For the deceleration-reaction time, an independent t-sample test was conducted to identify the difference in the means of the acceleration and deceleration reaction times. The null-hypothesis that the means are not equal was rejected ($P < 0.05$).

The ADRT as a function of gender, age group, driving experience, and driving intensity was also analyzed, as shown in figure 5. These driver characteristic are shown in table 2. As noted, the ADRT of females was larger than that of males. The ADRT also increased for all age groups of young, middle, and old drivers. The ADRT of the fairly experienced drivers is higher than that of the beginners and well experienced drivers.

VI. MODELING OF REACTION TIME

As previously mentioned, the BRT data were collected for three driving conditions: normal, surprised, and stationary. Besides the BRT, the ADRT data were also collected during each simulation run of the experiments. The BRT data were analyzed using a 3 x 2 x 3 x 2 x 9 x 3 repeated measures ANOVA: (a) with age (three levels), gender (two levels), driving experience (three levels), and driving intensity (two

TABLE II
DRIVER AND SCENARIO VARIABLES AND THEIR LEVELS FOR REPEATED MEASURES ANOVA

Variable	Level and Range		
	1	2	3
Age (years)	Young 18-24	Middle 25-54	Old 55+
Gender	Male	Female	n.a.
Driving Experience (years)	Beginner 0-5	Fairly experienced 6-20	Well experienced 21+
Driving Intensity (hrs/week)	Normal 0-20	Excessive 21+	n.a.
Scenario Type	Normal	Surprised	Stationary

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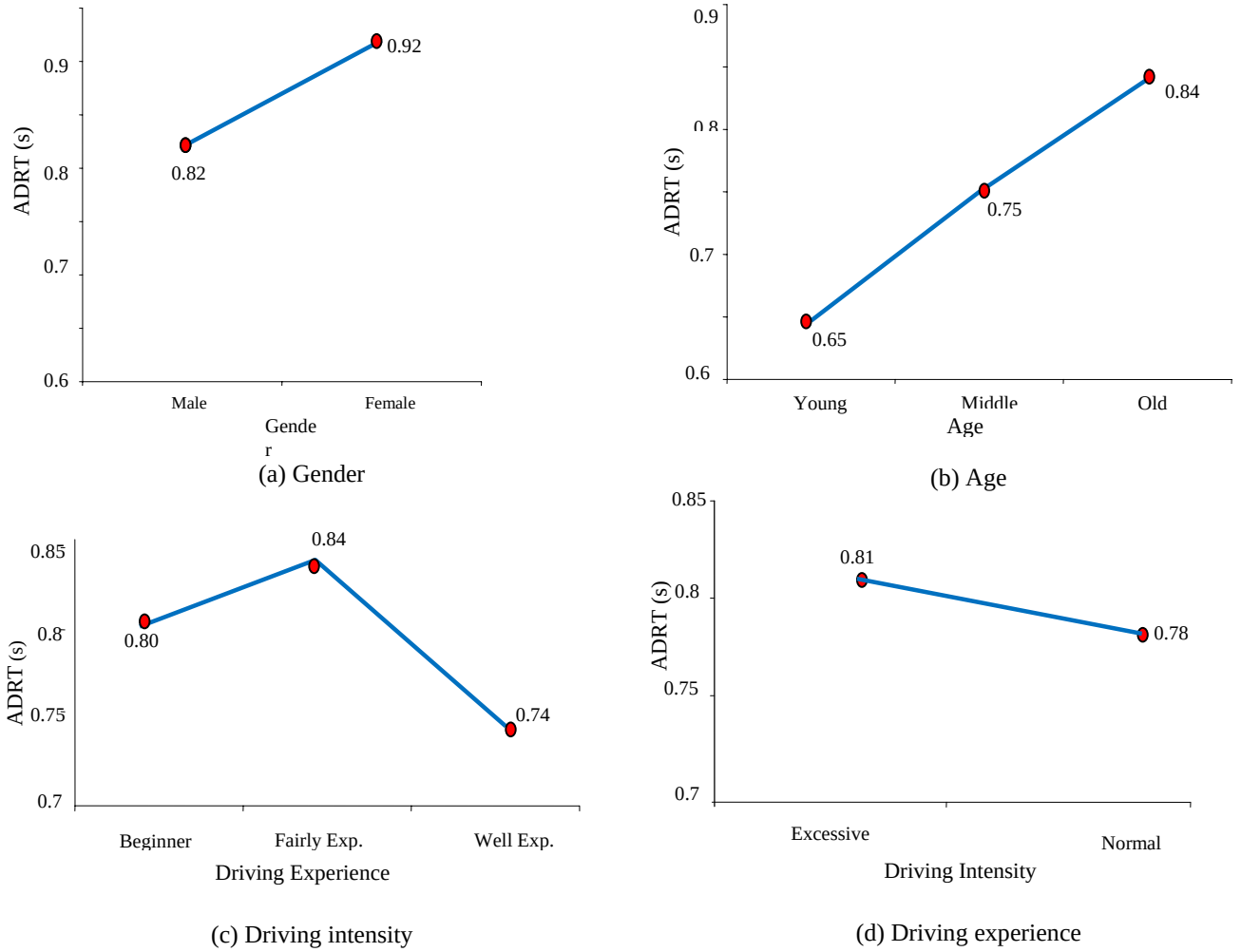


Fig. 5 Effect of driver factors on acceleration/deceleration reaction time

levels) as between-subjects factor and (b) with the speed-distance headway combinations (nine levels) and scenario type (three levels) as within-subject factors. The variables and their levels are shown in tables 2 and 3.

TABLE III
SPEED AND DISTANCE HEADWAY VARIABLES AND THEIR LEVELS FOR REPEATED MEASURES ANOVA

	Level								
Variable	1	2	3	4	5	6	7	8	9
V (km/h) - d (m) [a]	60-20	60-30	60-40	80-20	80-30	80-40	100-20	100-30	100-40
V (km/h) - d (m) [b]	60-10	60-20	60-30	80-10	80-20	80-30	100-10	100-20	100-30

[a] Normal and Stationary scenarios.
[b] Surprised scenario

There was a significant difference in the means of the BRT at each level of normal, surprised, and stationary scenarios. Therefore, an independent repeated measures ANOVA was conducted for each scenario. This analysis will help identify the independent variables that have significant effects on the BRT for each driving condition. The analysis revealed that speed, distance headway, age, and gender were significant factors that affect brake-reaction time in all scenarios.

Regression analysis was conducted to model the BRT for each driving condition. The independent variables were speed, distance headway, driver age, gender, driving experience, and driving intensity. The repeated measures ANOVA revealed several significant variables that affect the BRT at different driving conditions. Several combinations of variables were tested to develop models for the BRT for the three kinematic conditions.

The models were developed using the SPSS software. For the normal driving condition, two models were developed as follows,

$$BRT_n = 0.025\ Age + 0.401\ Gender \quad (Normal, Model\ 1) \quad (R^2 = 0.78) \quad (4)$$

$$BRT_n = 0.078\ Gender - 0.002\ V + 0.049\ d \quad (Normal, Model\ 2) \quad (R^2 = 0.97) \quad (5)$$

where BRT_n = brake-reaction time at normal driving condition (s), Age = age of the driver of the following vehicle (years), Gender = gender of the driver of the following vehicle (0 for males and 1 for females), V = speed of the following vehicle (km/h), and d = distance headway between the following and the lead vehicles (m).

The Age variable was significant only in Model 1, while V and d were significant only in Model 2. Model 2 is recommended here since it accounts for the speed and distance headway which are important variables in the calibration and validation of the car-following and rear-end collision warning algorithms. As expected, the BRT increases with the increase in distance headway and decreases as the speed increases. The positive sign of the Gender variable indicates that females are slower than males.

For the surprised and stationary scenarios, the developed BRT models are as follows,

$$BRT_{sr} = 0.001\ Age + 0.109\ Gender + 0.003\ V + 0.023\ d, \quad (Surprised) \quad (R^2 = 0.95) \quad (6)$$

$$BRT_{st} = 0.002\ Age + 0.035\ Gender + 0.001\ V + 0.017\ d, \quad (Stationary) \quad (R^2 = 0.96) \quad (7)$$

where BRT_{sr} and BRT_{st} = brake-reaction time for surprised and stationary scenarios (s), respectively. As noted, the BRT increases with the age, speed, and distance headway in both scenarios. The results of Eqs. 6 and 7 suggest that drivers may have difficulty in decision making at higher speeds in the stationary and surprised scenarios. The females are also slower in both of these scenarios.

Regression analysis was also conducted to model the acceleration/deceleration reaction time. Only age and gender were found to be significant variables. The developed model for the ADRT is as follows,

$$ADRT = 0.017\ Age + 0.159\ Gender, \quad (R^2 = 0.79) \quad (8)$$

where ADRT = acceleration/deceleration reaction time (s). As noted, the ADRT increases with the age and the positive sign of the Gender variable indicates that females are slower than males. In estimating the models of Eqs. 4-8, the driving experience and driving intensity were not found to be significant variables.

VII. CONCLUDING REMARKS

This study has explored the effect of the driver and situational factors on the driver reaction time and presented analytical models for BRT and ADRT which are necessary inputs for car-following algorithms. The driver factors include age, gender, driving experience, and driving intensity and the situational factors include speed, spacing, urgency, and expectancy. Based on this research the following comments are offered:

1) The results of this study have important theoretical and practical implications. The theoretical issues concern the different driver behaviour in the normal, surprised, and stationary conditions and the variables that influence the driver reaction time. The reaction time addressed in this study includes brake-reaction time and acceleration-deceleration reaction time. The practical issues concern the modeling of the driver reaction time in different driving situations and its application in car-following and rear-end collision warning algorithms. At higher speeds, for example 90 km/h, every hundredth of a second can reduce the stopping distance by 0.25 m. Therefore, every fraction of a second is important in modeling BRT in a car-following situation.
2) The results support the hypothesis that both urgency and expectancy have significant effects on the brake-reaction time. The age, gender, speed, and distance headway were found to be significant variables that affect BRT in the normal, surprised, and stationary conditions. However, age was not found to be a significant variable in predicting the BRT for the normal scenario when it was combined with gender, speed, and distance headway. The age and gender variables were also found to be significant in predicting the acceleration/deceleration reaction time. The study also supports the hypothesis that BRT increases with age and that females are slower than males. The trend of both age and gender is the same in the analysis of BRT and ADRT.
3) For the situational factors, the BRT decreases with the increase of speed in the normal scenario and increases with the increase of speed in the surprised and stationary scenarios. This variation of the speed behavior is most likely due to the braking behavior of the lead vehicle. As previously mentioned, the stationary scenario also acts like a surprise scenario. Therefore, the effect of speed (BRT increases with the speed) in both of these scenarios is the same. It was also found that the BRT increases with the increase in distance headway in all scenarios. The repeated measures ANOVA and regression analysis do not support the hypothesis that driving experience and driving intensity are significant variables that affect the brake-reaction time in a normal, surprised, or stationary scenario.
4) The results for the effect of age and gender on BRT agree with those of Broen and Chiang [11] and Lings [14], respectively. The results for the effect of speed and distance headway agree with those of Schweitzer et al. [21]. Besides exploring these effects, the present study has presented analytical models that are necessary for car-following analysis. Specifically, The BRT model for the normal scenario and ADRT model will be useful for

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modeling the car-following simulation algorithm. The surprised and stationary car-following situations are more likely to contribute to a rear-end collision situation compared to normal situations in which the lead vehicle braking behaviour is within the normal deceleration rates. Therefore, the BRT models for the surprised and stopped conditions will be useful in modeling the rear-end collision warning systems.

ACKNOWLEDGMENTS

This research was financially supported by the Natural Sciences and Engineering Research Council of Canada and an Ontario Graduate Scholarship.

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