Drivers' Rear End Collision Avoidance Behaviors under Different Levels of Situational Urgency

Xuesong Wang[a,b*], Meixin Zhu[a], Ming Chen[b], Paul Tremont[b]

[a]The Key Laboratory of Road and Traffic Engineering, Ministry of Education, Shanghai, 201804, China

[b]School of Transportation Engineering, Tongji University, Shanghai, 201804, China

**Corresponding Author. Tel: +86-21-69583946. E-mail address: wangxs@tongji.edu.cn*

Abstract:

Rear-end collisions have been estimated to account for 20 to 30 percent of all crashes, and about 10 percent of all fatal crashes. A thorough investigation of drivers' collision avoidance behaviors when exposed to rear end collision risks is needed to help guide the development of effective countermeasures. Urgency or criticality of the situation affects drivers' collision behavior, but has not been systematically investigated. A high fidelity driving simulator was used to examine the effects of differing levels of situational urgency on drivers' collision avoidance behaviors. Drivers' braking and steering decisions, perception response times, throttle release response times, throttle to brake transition times, brake delays, maximum brake pedal pressures and peak decelerations were recorded under lead vehicle decelerations of 0.3 g, 0.5 g, and 0.75 g and under headways of 1.5 s and 2.5 s. Results showed 1) as situational urgency increased, drivers released the accelerator and braked to maximum more quickly; 2) the transition time between initial throttle release and brake initiation was not affected by situational urgency; 3) at low situational urgency, multi-stage braking behavior led to longer delays from brake initiation to full braking. These findings show that effects of situational urgency on drivers' response times, braking delays, and braking intensity should be considered when developing forward collision warnings systems.

Keywords: Rear-end Collisions; Collision Avoidance Behavior; Perception Response Time; Braking Delay; Situational Urgency.

1. Introduction

In the US, rear-end collisions account for approximately 32% of all crashes and 6% of fatal crashes (Traffic Safety Facts, 2013), in Japan, about 35% of all crashes (Watanabe and Ito, 2007), and in Germany about 22% of all crashes (German Federal Statistical Office, 2009). In Shanghai, China, Wang et al. (2011) reported that rear-end crashes accounted for about 20% of all crashes, but 49% of elevated expressway crashes and 67% of tunnel crashes.

Rear-end collisions are usually attributed to 1) insufficient headway, 2) late brake response, and 3) insufficient brake force (Winsum and Heino, 1996). A thorough investigation of how drivers respond and brake in collision imminent situations is needed to improve FCW systems.

Perception Response Time (PRT), a component of collision avoidance behaviors, is defined as the time required to perceive, interpret, decide, and initiate a response to some stimulus, e.g., sudden brake of the lead vehicle (LV) (Sohn and Stepleman, 1998). PRT is an important component of Forward Collision Warning (FCW) timing algorithms (Kiefer et al., 1999) and is essential for accident reconstruction analyses (Ising et al., 2012). Previous research has reported PRTs from 0.5 to 10 sec for various tasks (Muttart, 2005). This large range is attributable to the dependence of PRT on a myriad of factors including expectation, age, gender, and cognitive load (Green, 2000).

One key variable affecting PRTs is urgency or criticality of the situation (Summala, 2000). Situational urgency has been measured using two types of indicators. One type characterizes situational urgency by the initial state of the scenario, e.g., the following distance, headway, and Time to Collision (TTC) at LV brake onset. Another type characterizes situational urgency by the rate of LV deceleration.

Using the initial state urgency indicator, Liebermann et al. (1995) and Schweitzer et al. (1995) tested effects of both speed and following distance on PRT. Neither study found an effect of speed, however both studies found shorter following distances (6 m vs. 12 m) produced faster responses. Summala et al. (1998) tested drivers' PRTs under 4 different initial distance and speed combinations (15 m, 30 km/h; 30 m, 30 km/h; 30 m, 60 km/h; 60 m, 60 km/h). They also found no speed effect. PRT increased with increases in following distance. Aust et al. (2013) reported that PRT was overall significantly longer in the long initial headway (at LV brake onset) condition. Based on a meta-analysis of several experimental studies, Engström (2010) found that PRT was almost linearly correlated with initial headway, that is, the shorter the initial headway, the faster the response. Using the rate of LV deceleration urgency indicator, Hulst (1999) tested the effect of LV deceleration rate on PRT, and found the PRT for fast decelerations (2 m/s^2) was shorter than for slow decelerations (1 m/s^2).

To date, few studies, e.g., Lee et al. (2002), manipulated situational urgency using both the initial state and deceleration rate urgency indicators. Considering that urgency as defined by an initial state is operationally different from urgency defined by deceleration rate, it is advantageous to consider both definitions to realize a full understanding of the effects of situational urgency on PRT.

Previous studies concerning the effects of situational urgency focused on drivers' response times before braking by capturing brake/perception response times or accelerator release times. These measures reflect what drivers do before braking, but tell us nothing about what drivers do with the brake after the foot gets to the pedal. However, studies on braking behaviors have consistently shown that a driver-related delay was observed between initial brake application and full emergency braking (Ising et al., 2012; Hirose et al., 2008; Perron et al., 2001; Kiesewetter et al., 1999; Yoshida et al., 1998). Also, studies have shown that drivers, especially unskilled ones, often fail to apply sufficient force on the brake pedal in an emergency (Kassaagi et al., 2003; Roody, 2011). Therefore, investigating effects of situational urgency on braking delay and intensity is necessary to fully understand drivers' braking behaviors.

The objective of this study was to quantify the response times and braking behaviors drivers exhibit under varying levels of situational urgency. Driving simulators are ideal for performing these kinds of studies because of their ability to systematically vary perceived urgency while capturing quantitative data on relevant aspects of driver and system performance (Boyle and Lee, 2010). In this study, the Tongji University Driving Simulator was used to generate different urgency levels by varying headway and LV deceleration while capturing data on perception response times (PRT), throttle release response times, throttle to brake transition times, brake delays, maximum brake pedal pressures and peak decelerations. The relationships uncovered between situational urgency and drivers' collision avoidance behavior measures can provide information that can be used to develop improved FCW systems.

2. Methods

2.1.Experimental Design

2.1.1. Independent Variables

A three-factor within-subjects design was used. The independent variables were LV deceleration, initial headway and exposure. Three levels of LV deceleration (0.3 g, 0.5 g, and 0.75 g) and two levels of initial headway (1.5 sec and 2.5 sec) were combined to produce rear-end scenarios with different urgency levels. The order of presentation was counterbalanced across drivers using a pseudo-randomization procedure described by Curry et al. (2005). This procedure resulted in 2×3=6 trials experienced by each participant. The exposure referred to the presentation order of the trial within a subject, and had 6 levels, and aimed to test whether drivers behaved differently across the 6 trials. A description of the independent variables is presented in TABLE 1.

Effects of driver age, gender, and driving experience were considered, but were not reported in this research. All the decelerations mentioned in this article refer to absolute values of deceleration rates and therefore no minus signs were added.

TABLE 1 Description of Independent Variables

Independent Variables	Conditions
Initial headway (within)	1.5 sec; 2.5 sec
LV deceleration (within)	0.3 g; 0.5 g; 0.75 g
Exposure (within)	1st trial; 2nd trial; 3rd trial; 4th trial; 5th trial; 6th trial

2.1.2. Dependent Variables

Ten dependent variables were used to measure drivers' collision avoidance behaviors. Each is defined below:

1) *Number of Rear-end Collisions*: A collision was defined as the SV striking the rear or side of the LV. Each recorded collision was verified by a second researcher.

2) *Perception Response Time* (*PRT*): Time between LV brake onset and SV brake/steering onset. If both braking and steering maneuvers were observed during the conflict interval, then the PRT was calculated with reference to the first avoidance maneuver.

3) *Time to Initial Throttle Release* (T_{Init}): Time between LV brake onset and the moment when the SV started to release the throttle pedal.

4) *Time to Final Throttle Release* (T_{Final}): Time between the initiation and complete release of the SV throttle pedal.

5) *Time to Initiate Braking* (T_{brake}): Time between complete release of the SV throttle and initiation of pressure on the SV brake pedal.

6) *Time to 25% Brake* ($T_{25\%Brake}$): Time between initiation of pressure on the SV brake pedal and the moment when the SV brake pedal pressure reached 25% of the maximum force that can be placed on the brake pedal (25 daN), if applicable.

7) *Time to 50% Brake* ($T_{50\%Brake}$): Time between initiation of pressure on the SV brake pedal and the moment when the brake pedal pressure reached 50% of the maximum brake pedal force limit (25 daN) if applicable.

8) *Time to Maximum Brake* ($T_{MaxBrake}$): Time between initiation of pressure on the SV brake pedal and the moment the SV brake pedal force reached the maximum value observed during the braking event.

9) *Maximum Brake Pedal Pressure* ($Brake_{max}$): The maximum value of brake pedal pressure observed during the braking event, which is less than or equal to 25 daN.

10) *Peak Deceleration* (Dec_{peak}): The maximum absolute value of SV deceleration rate observed during the braking event.

2.2.Sequential Timing of Events and Measurements

Fig. 1 shows the sequence of timed events and example curves for vehicle speed, acceleration, throttle, steering wheel angle, and braking pedal pressure as they change during a collision avoidance episode.

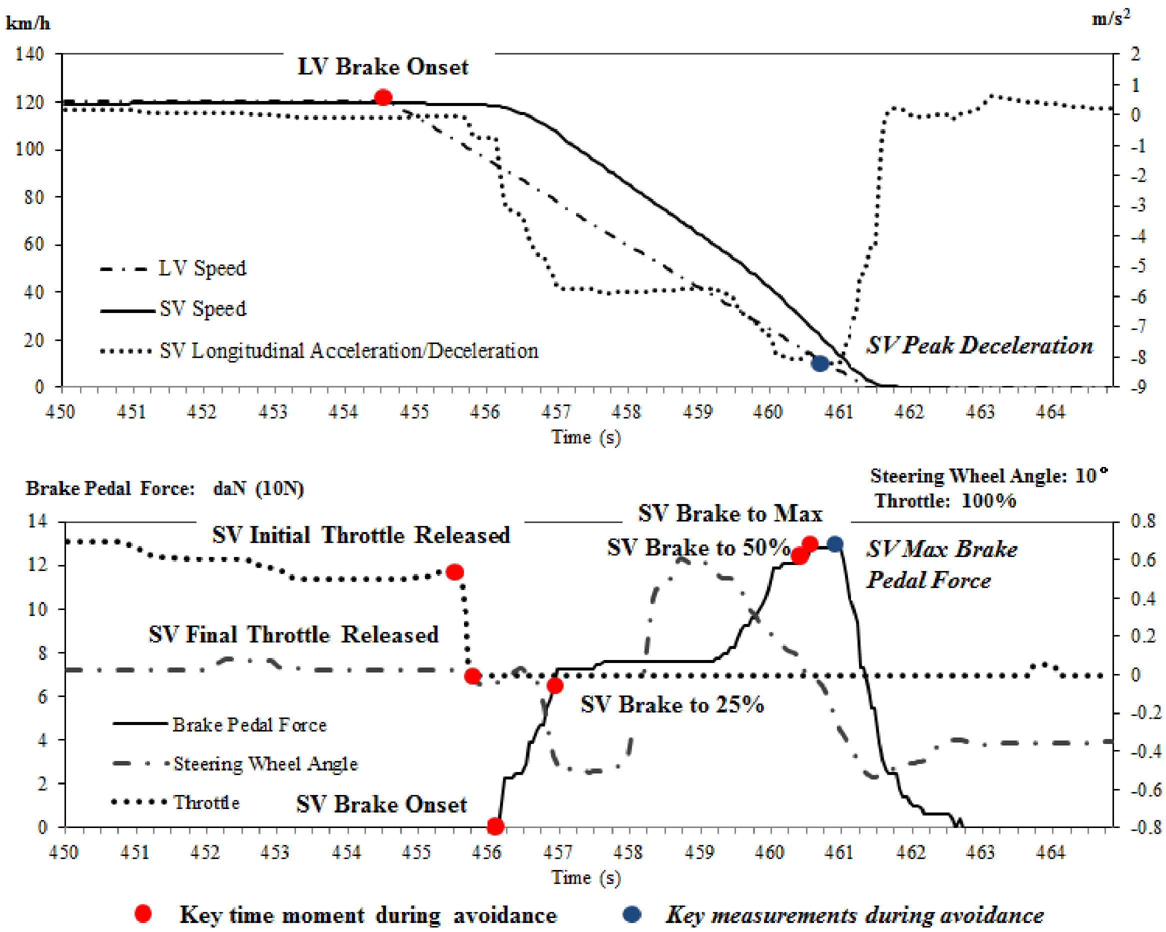


Fig. 1 A Typical collision avoidance event sequence

Based on the key time moment in Fig. 1, the measures quantifying drivers' response times and braking behaviors are shown in Fig. 2.

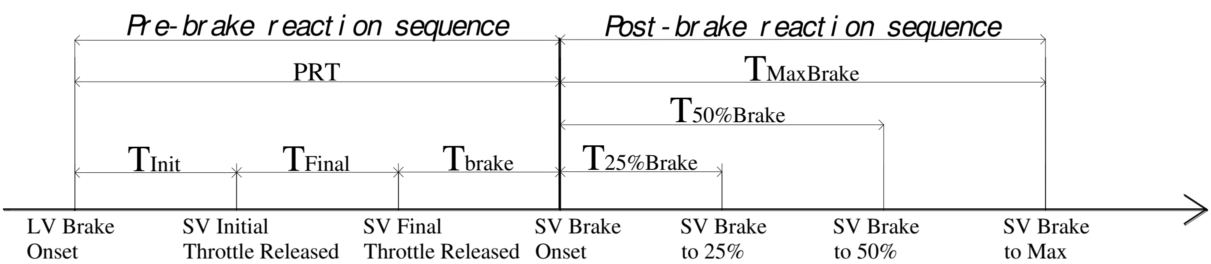


Fig. 2 Measures quantifying drivers' behavior during a rear-end collision avoidance event

2.3.Participants

Six females and 23 males, (ages 23–54, M = 33.2, SD = 8.3), who possessed valid driver's licenses and had at least one year and 10,000 kilometers of driving experience recruited from the population of drivers in Shanghai served as participants. One participant showed symptoms of simulator sickness and was replaced. Concerning the male female disparity in China—female drivers accounted for 23.48% of all drivers in 2014, and so our male female ratio was in line with that. Drivers older than 54 were avoided because the average retirement age was 55 in China when the experiment was conducted, and most retirees drive infrequently after they stop working.

2.4.Apparatus

Fig. 3 shows the Tongji University driving simulator used in this study. This simulator, currently the most advanced in China, incorporates a fully instrumented Renault Megane III vehicle cab in a dome mounted on an 8 degree-of-freedom motion system with an X-Y range of 20 × 5 meters. An immersive 5 projector system provides a front image view of 250° × 40° at 1000 × 1050 resolution refreshed at 60 Hz. LCD monitors provide rear views at the central and side mirror positions. SCANeR^{TM} studio software (OKTAL) presented the simulated roadway and controlled a force feedback system that acquired data from the steering wheel, pedals and gear shift lever. The transmission of the Renault Megane III vehicle was automatic, and the braking system was a non-ABS. The overall performance of this driving simulator was validated using three tests: simulator sickness, stop distance, and traffic sign size. Test results showed that the driving simulator satisfied the three criteria (i.e. at least 75% of participants show no simulator sickness, stop the car within 2 meters of a designated stop line and judge the realism of the traffic sign size) for validation.

Fig. 3 Tongji University driving simulator

2.5. Procedure

2.5.1. Orientation Phase

On arriving at the driving simulator facility, participants were given general information about the research and asked to read an informed-consent document. They then completed a questionnaire covering demographics, driving history, and simulator sickness. Following this, they were briefed on the operation of the simulator vehicle, and told they would perform a normal vehicle-following task in the simulator vehicle.

Participants were next given a few minutes to gain familiarity with the simulator and instructed to pay particular attention to the feel of the steering wheel, accelerator pedal, and brake pedal. Next they were given a 7-minute practice drive during which they experienced a following exercise and a braking exercise. For the following exercise, drivers were asked to maintain a distance of between 60 m and 80 m behind a white LV on a straight road while the actual distance between their vehicles and the LV was displayed on a forward screen. The braking exercise came immediately after the following exercise. Participants were asked to accelerate to 100 km/h and then to stop the car behind a stationary truck. Each subject performed this action twice. After the practice drive, participants were given a 5-minute break. If they showed no signs of simulator sickness, they continued with the actual test phase.

2.5.2. Test Phase

Participants resumed driving on the inner lane of a two-lane freeway under good weather daytime conditions with light traffic (see Fig. 4-b), and were asked to accelerate to the target speed (120 km/h) at the beginning of the scenario. To minimize distractions, traffic was not present in the same direction of the SV, although for realism, light traffic was presented in the opposite direction. After about 2 minutes, a white lead vehicle (LV) moved in front of the SV. The LV was programmed to operate at a constant speed of 120 km/h, and participants were again asked to follow the lead vehicle at distance of 60 m to 80 m. The LV was programmed to make 6 unpredicted full stops with brake lights on, at prearranged initial headway settings of 1.5 sec and 2.5 sec, and at varying intervals. To reduce the predictability of LV stops, there were two cases during the test phase where LV slowed down but with small deceleration rates of 0.02 g to 0.1 g. When the LV was triggered to stop, if the control program determined the SV was not within the specified headway range, a “Speed Up” message was displayed on the screen until the SV reached the targeted headway. To prevent drivers from anticipating collision situations in association with “Speed Up” messages, instances were included in the experiment in which the “Speed Up” message was displayed but without a subsequent sudden LV brake. A minimum period of 5 seconds was then introduced during which it was confirmed that the participants were following the LV steadily. Once confirmed, the LV would come to a stop at the programmed deceleration rate. It should be noted that all the programmed events occurred on flat straight roads, thus eliminating the effects of horizontal curves and longitudinal slopes on drivers’ braking and steering. Test phases were completed after 6 full stops were made, and required about 30 minutes. A post-simulation survey of participants conducted showed that more than 60% of drivers said the vehicle dynamics, motion systems, and visual and audio systems of the driving simulator had a high level of realism.

Throughout the experiment, participants were visually monitored using four video cameras (see Fig. 4-a).

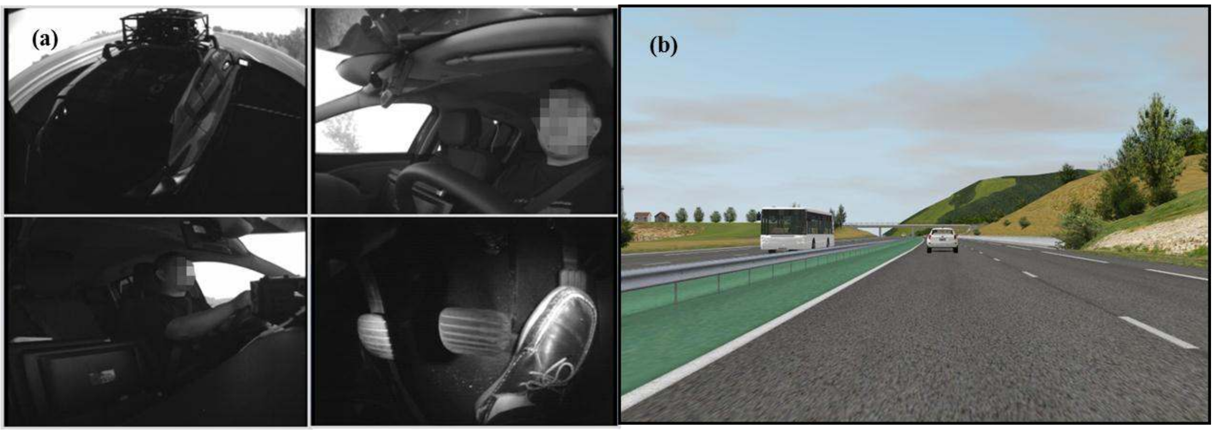


Fig. 4 Video monitor displays (a) and experiment scenario (b)

3. Results

3.1.Data Analysis

The overall reaction sequence and avoidance maneuver data were recorded at a frequency of 20 Hz using SCANeR^{TM} Studio software. A database containing information for 173 (29×6－1) simulated rear-end scenarios (one missing-data scenario was excluded) was created. Further examination of the data revealed that in 32 of the scenarios, drivers released the accelerator before the LV began to brake, making those trials not appropriate for pooling with trials when this did not occur. Therefore, 141 simulated rear-end scenarios were used in the analysis.

It should be noted that a minimum 5-second period was imposed between the conditions required to have the LV stop and the actual LV brake onset. Drivers' headway at LV brake onset thus varied around the initial requirement of 1.5 and 2.5 sec, and was categorized into three levels: Short (less than 1 sec) Medium (1 sec up to 1.5 sec), and Long (1.5 to 2.5 sec) for subsequent analysis. Analyses of Variance (ANOVA) were performed to determine whether drivers' response times and braking behaviors differed significantly under these varying levels of situational urgency. A series of post-hoc analyses using Tukey's (Tukey, 1949) method was then conducted to determine differences between drivers' response times and braking behaviors under various levels of situational urgency. The statistical significance level was set at $\alpha = 0.05$.

3.2.Collision Avoidance Maneuvers and Their Effectiveness

Drivers were free to choose their preferred collision avoidance maneuvers in the various rear-end collision scenarios: braking only, steering only, or both steering and braking. As shown in Fig. 5, of the 141 valid rear-end scenarios, 121 (85.82%) scenarios involved using a brake-only maneuver, and 20 (14.18%) scenarios involved a brake-with-steering maneuver. No drivers used a steering-only maneuver. Of those scenarios with a brake-only maneuver, 29.75% preceded collisions, while braking-with-steering scenarios did not precede any collisions.

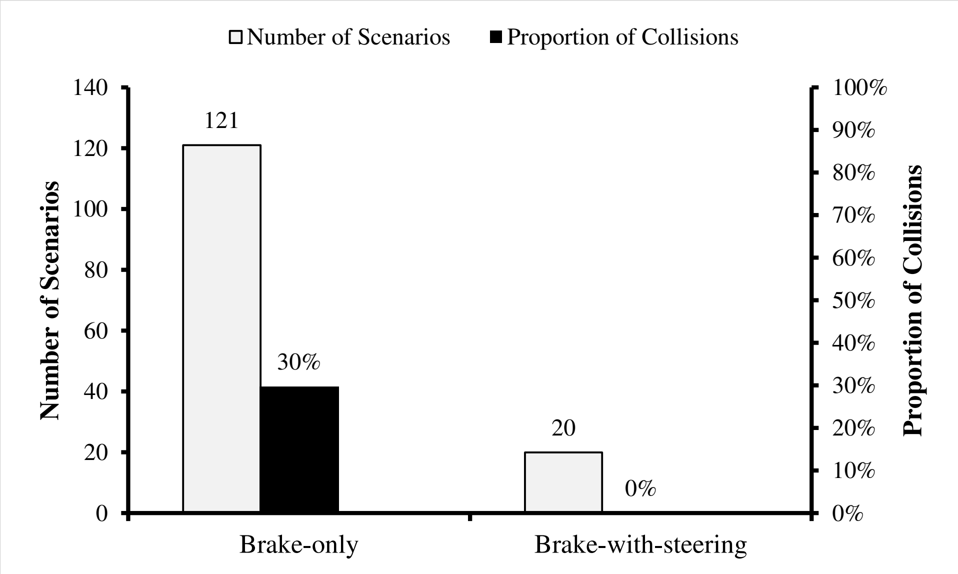
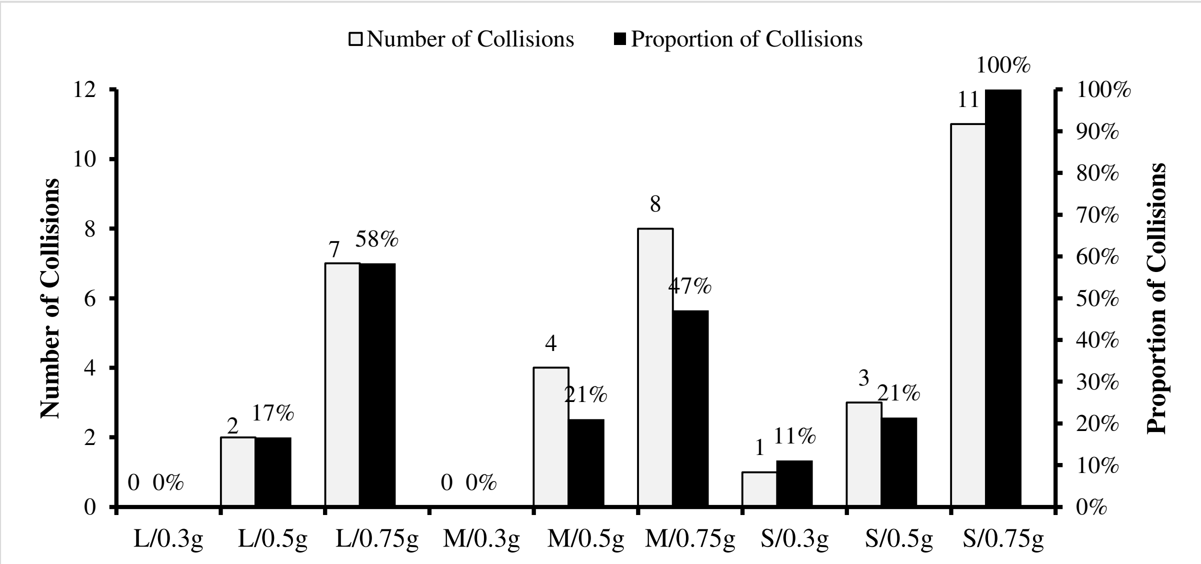


Fig. 5 Number of scenarios and proportion of all collisions of each collision avoidance maneuver

Fig. 6 shows the number and percentage of observed collisions for the 121 brake-only scenarios under different levels of situational urgency as established by differing LV decelerations and initial headways. Most of the brake-only collisions (about 72%) occurred under LV deceleration of 0.75 g.



Note: "S" denotes initial headway <1 s, "M" from 1 to 1.5 s and "L" from 1.5 to 2.5 s, as it is for other figures.

Fig. 6 Observed collisions for brake-only cases (Initial headway condition/LV deceleration in g's)

3.3.Perception Response Time

Fig. 7 shows mean Perception Response Time (PRT) of the drivers under different LV deceleration and initial headway conditions. As can be seen in the figure, drivers responded faster when the LV deceleration (absolute value, as it is for other decelerations mentioned in this paper) increased or the initial headway decreased. ANOVA revealed significant main effects of initial headway ($F_{[2,99]}$=26.54, p<0.0001), LV deceleration ($F_{[2,99]}$=6.47, p=0.0023) and exposure ($F_{[5,99]}$=4.81, p=0.0006) on PRT.

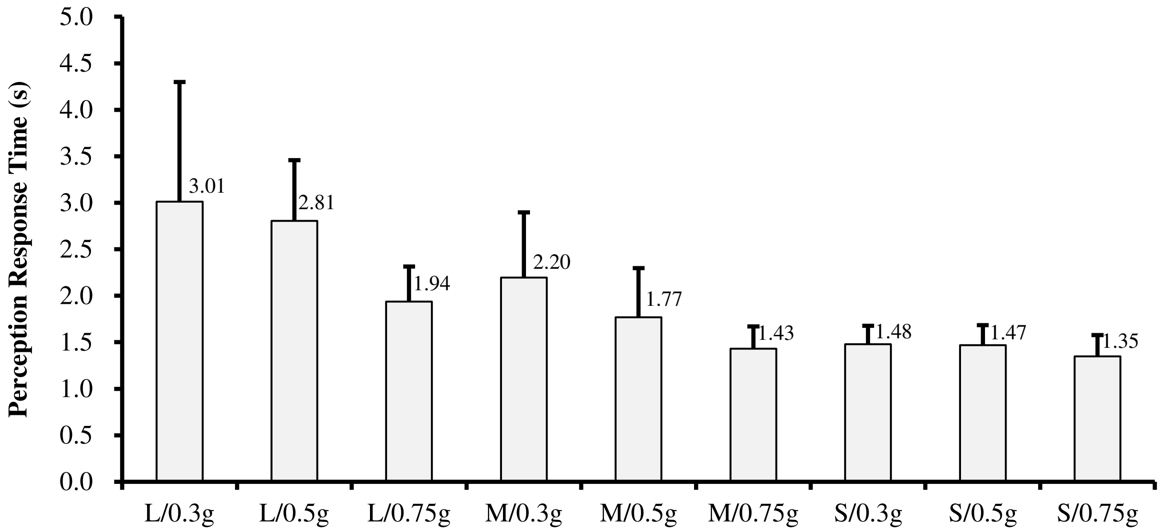


Fig. 7 Perception response time (Initial headway condition/LV deceleration in g's)

Post-hoc analyses were done to test the significance of Least Squares Means differences (LSM) of PRT for each paired conditions. The post-hoc analysis of PRT is shown in TABLE 2. Significant differences (p-value < 0.05) are in bold. The difference of PRT for long and short headway conditions was quite large (0.97 sec).

TABLE 2 Post-hoc analysis for PRT (sec)

	Paired Condition					
	L&M*	L&S	M&S	0.3g&0.5g	0.3g&0.75g	0.5g&0.75g
Difference	0.5865	0.9792	0.3927	0.3146	0.5236	0.209
P-Value	**<0.0001**	**<0.0001**	**0.0047**	**0.0219**	**0.006**	0.4277

** Difference of PRT for paired condition L&M denotes PRT of long initial headway condition minus that of medium headway condition, in the same way for other paired conditions.*

For the exposure factor, the Post-hoc analysis showed that drivers responded significantly more slowly in the first trial than in the remaining trials, with an average PRT difference of 0.67 sec. The differences of PRT among trials 2–6 were not significant.

3.4.Reaction Sequence

3.4.1. Pre-brake Reaction Sequence

As illustrated in Fig. 2, each driver's reaction sequence was decomposed into a pre-brake reaction sequence and a post-brake reaction sequence. The pre-brake reaction sequences were reflected in Time to Initial Throttle Release (T_{Init}), Time to Final Throttle Release (T_{Final}) and Time to Initiate Braking (T_{brake}) measures. Fig. 8 shows the mean of pre-brake reaction sequences. T_{Init} decreased when the initial headway decreased; T_{Final} decreased when LV deceleration increased, while T_{brake} did not change systematically along with the initial headways or LV decelerations.

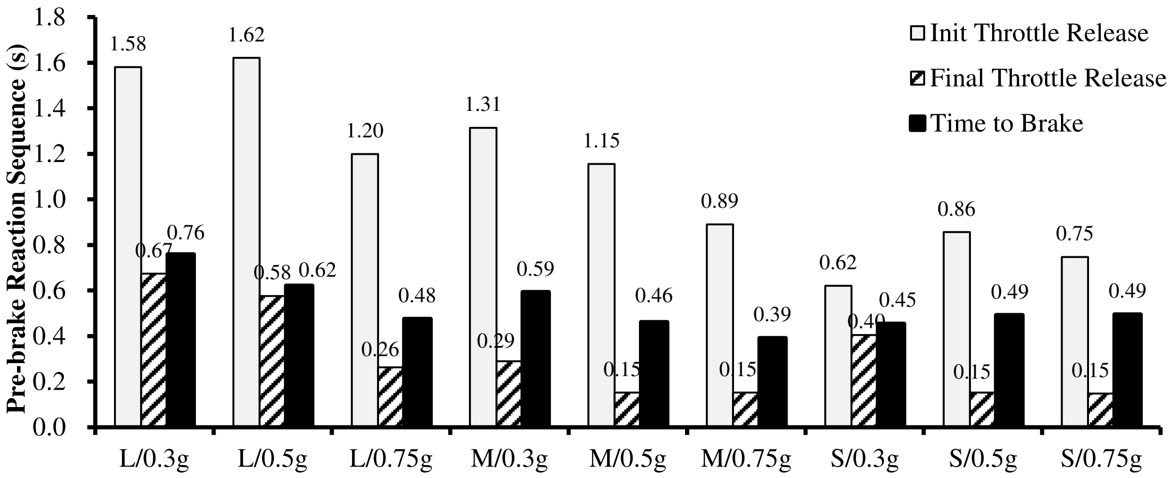


Fig. 8 Pre-brake reaction sequence (Initial headway condition/LV deceleration in g's)

The ANOVA revealed a significant main effect of initial headway ($F_{[2,99]}$=7.95, p=0.0006) on T_{Init}. Post-hoc analysis for T_{Init} is shown in TABLE 3. However, the ANOVA revealed no significant main effects on T_{Final} and T_{brake}. The average value across all observations for T_{Final} and T_{brake} were 0.30 sec and 0.52 sec respectively. Fitch et al. (2010) recorded a mean T_{brake} of 0.33 sec in their test-track study where drivers encountered a barricade that inflated out of the road when TTC reached 2.5 sec.

TABLE 3 Post-hoc analysis for T_{Init} (sec)

	Paired Condition					
	L&M	L&S	M&S	0.3g&0.5g	0.3g&0.75g	0.5g&0.75g
Difference	0.2712	0.6197	0.3485	-0.02119	0.2234	0.2446
P-Value	0.1484	**0.0004**	**0.0386**	0.9872	0.5004	0.4427

3.4.2. Post-brake Reaction Sequence

Drivers' post-brake behaviors were examined by Time to 25% Brake ($T_{25\%Brake}$), Time to 50% Brake ($T_{50\%Brake}$) and Time to Maximum Brake ($T_{MaxBrake}$). Fig. 9 shows drivers' post-brake reaction sequences. As can be seen, even in the most urgent situation (S/0.75g condition), a 0.92 sec delay between brake initiation and full braking was observed. $T_{25\%Brake}$ and $T_{50\%Brake}$ decreased as the LV deceleration increased or the initial headway decreased. $T_{MaxBrake}$ decreased as LV deceleration increased, while it did not show systematic changes under different initial headways.

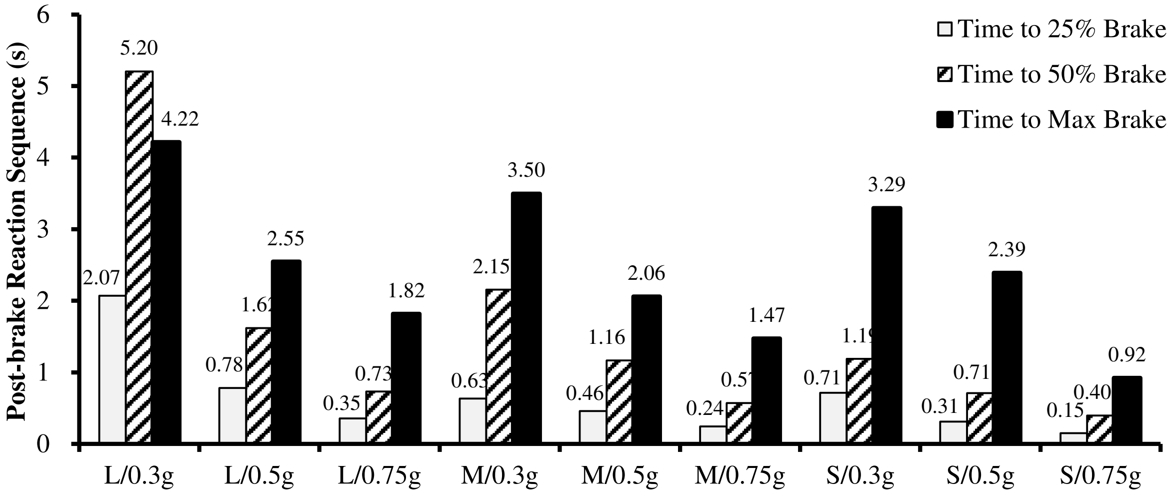


Fig. 9 Post-brake reaction sequence (Initial headway condition/LV deceleration in g's)

ANOVA showed that initial headway ($F_{[2,92]}$=5.73, p=0.0045) and LV deceleration ($F_{[2,92]}$=13.32, p<0.0001) both have significant main effects on $T_{25\%Brake}$. Post-hoc analysis for $T_{25\%Brake}$ is shown in TABLE 4.

TABLE 4 Post-hoc analysis for $T_{25\%Brake}$ (sec)

	Paired Condition					
	L&M	L&S	M&S	0.3g&0.5g	0.3g&0.75	0.5g&0.75g
Difference	0.4937	0.526	0.03235	0.6984	0.8272	0.1288
P-Value	**0.0089**	**0.0102**	0.9768	**<0.0001**	**0.0007**	0.8155

The main effects of initial headways ($F_{[2,62]}$=7.25, p=0.0015) and LV decelerations ($F_{[2,62]}$=9.81, p=0.0002) were significant on $T_{50\%Brake}$. Post-hoc analysis for $T_{50\%Brake}$ is shown in TABLE 5.

TABLE 5 Post-hoc analysis for $T_{50\%Brake}$ (sec)

	Paired Condition					
	L&M	L&S	M&S	0.3g&0.5g	0.3g&0.75g	0.5g&0.75g
Difference	1.1481	1.5924	0.4443	1.7169	1.989	0.2721
P-Value	**0.024**	**0.0011**	0.2162	**0.0002**	**0.0008**	0.7549

In addition, ANOVA showed significant main effects of LV deceleration ($F_{[2,98]}$=11.30, p<0.0001) on $T_{MaxBrake}$. Post-hoc analysis for $T_{MaxBrake}$ is shown in TABLE 6. The difference of $T_{MaxBrake}$ for LV deceleration of 0.3 g and 0.75 g is quite large (2.5 sec).

TABLE 6 Post-hoc analysis for $T_{MaxBrake}$ (sec)

	Paired Condition					
	L&M	L&S	M&S	0.3g&0.5g	0.3g&0.75g	0.5g&0.75g
Difference	0.1754	0.1844	0.00902	1.413	2.5703	1.1573
P-Value	0.9153	0.9213	0.9998	**0.0031**	**0.0001**	0.1378

3.5.Maximum Brake Pedal Pressure/Peak Deceleration

Fig. 10 shows the mean of maximum brake pedal force ($Brake_{max}$) and peak deceleration (Dec_{peak}). As can be seen from the figure, $Brake_{max}$ and Dec_{peak} increased as the LV deceleration increased. For different initial headway conditions, no obvious differences were observed.

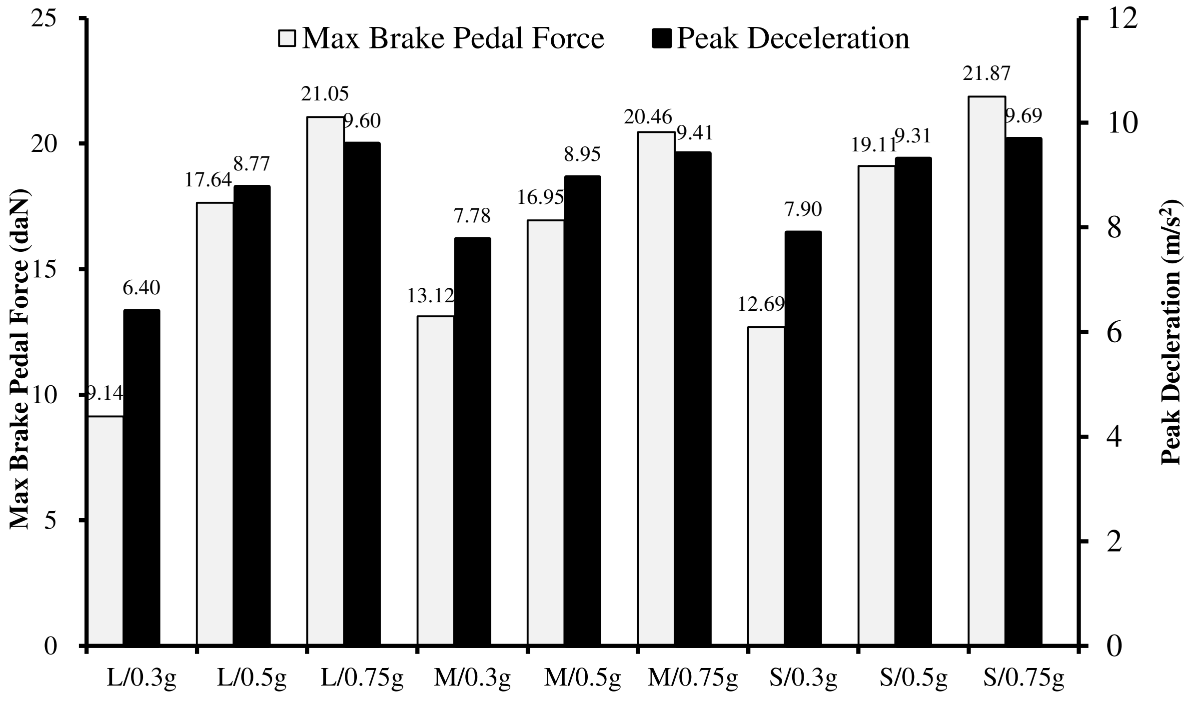


Fig. 10 Maximum brake pedal pressure and peak deceleration (Initial headway condition/LV deceleration in g's)

The ANOVA revealed a significant main effect of LV deceleration on $Brake_{max}$ ($F_{[2,98]}$=50.38, p<0.0001). Post-hoc analysis for $Brake_{max}$ is shown in TABLE 7. The obtained $Brake_{max}$ for L/0.5g condition was 17.64 daN, which is consistent with Fitch et al. (2010), who reported a mean $Brake_{max}$ of 16 daN when drivers encountered a surprise barricade in a test track when TTC reached 2.5 sec.

TABLE 7 Post-hoc analysis for $Brake_{max}$ (daN)

	Paired Condition					
	L&M	L&S	M&S	0.3g&0.5g	0.3g&0.75g	0.5g&0.75g
Difference	−1.7891	−1.7496	0.03951	−6.2948	−11.2154	−4.9207
P-Value	0.1487	0.2328	0.9991	**<0.0001**	**<0.0001**	**0.0004**

The ANOVA revealed significant main effects of both initial headway ($F_{[2,99]}$=5.60, p=0.0050) and LV deceleration ($F_{[2,99]}$=25.50, p<0.0001) on Dec_{peak}. Post-hoc analysis for Dec_{peak} is shown in TABLE 8.

TABLE 8 Post-hoc analysis for Dec_{peak} (m/s^2)

	Paired Condition					
	L&M	L&S	M&S	0.3g&0.5g	0.3g&0.75g	0.5g&0.75g
Difference	-0.8903	-0.9881	-0.0978	-1.5216	-2.5377	-1.0161
P-Value	**0.0109**	**0.0107**	0.943	**<0.0001**	**<0.0001**	**0.038**

3.6.Summary of Results

TABLE 9 summarizes the descriptive statistics for the dependent variables. For all the time-based metrics, the means are larger than the medians, indicating a right-skewed distribution.

TABLE 9 Statistical summary of dependent variables

Variable	**Mean**	**Median**	**Standard Deviation**	**N**	**Min**	**Max**
PRT (sec)	1.93	1.62	0.81	141	0.96	5.56
T_{Init} (sec)	1.12	1.01	0.69	141	0.00	3.95
T_{Final} (sec)	0.30	0.15	0.46	141	0.00	3.28
T_{brake} (sec)	0.52	0.46	0.23	140	0.25	1.82
$T_{25\%Brake}$ (sec)	0.57	0.25	0.87	134	0.03	5.00
$T_{50\%Brake}$ (sec)	1.01	0.56	1.23	103	0.05	5.71
$T_{MaxBrake}$ (sec)	2.39	1.62	2.13	140	0.10	10.01
$Brake_{max}$ (daN)	17.13	17.00	6.37	140	3.90	25.00
Dec_{peak} (m/s^2)	8.71	9.45	1.72	141	1.11	11.12

TABLE 10 summarizes the main effects of initial headway and LV deceleration on drivers' collision avoidance behaviors. As can be seen, the perception-response process (PRT, T_{Init}) is mainly affected by initial headway, and the braking behavior is mainly affected by LV deceleration, while the transition process (T_{Final}, T_{brake}) is affected by neither initial headway nor LV deceleration. The significant effect of exposure on PRT indicated that a learning effect was observed in trials 2-6. This learning effect only had an impact on drivers' cognitive activities (PRT), rather than the subsequent physical activities because effects of exposure were not observed for other dependent variables.

TABLE 10 Summary of main effects of initial headway and LV deceleration (*P<0.05*)

	Variable								
Factor	PRT	T_{Init}	T_{Final}	T_{brake}	$T_{25\%Brake}$	$T_{50\%Brake}$	$T_{MaxBrake}$	$Brake_{max}$	Dec_{peak}
Initial headway	√	√			√	√			√
LV deceleration	√				√	√	√	√	√
Exposure	√								

Note: " √" denotes significant main effects of the factor on the corresponding variable were observed.

4. Discussion

4.1. Decision to Brake only or to Brake and Steer

A lower crash rate was observed for scenarios when drivers reacted by both braking and steering. Although a possible benefit of brake-with-steering in avoiding the collision was shown, only 12.15% of the 141 analyzed rear-end scenarios were observed using this maneuver. This is consistent with the findings reported in the literature review by Adams (1994), in which he found that drivers are more likely to brake than to steer in collision avoidance situations. According to Adams (1994), the possible reason for the low percentage of steering maneuvers may be that 1) drivers' tendency to maintain their own lanes of travel, 2) their lack of knowledge of about alternative maneuvers and 3) the handling capability of their vehicles.

Fig. 11 shows the proportion of scenarios with brake-with-steering maneuver under different LV decelerations. As can be seen, as the LV deceleration increased, the proportion of scenarios with brake-with-steering maneuver also increased. Similarly, Limpert and Gamero (1974), using accident data, found that as speed increases, the number of drivers who attempt to avoid the collision by steering also increases. These two findings suggest that drivers might be more likely to use a steering maneuver at high risk situations.

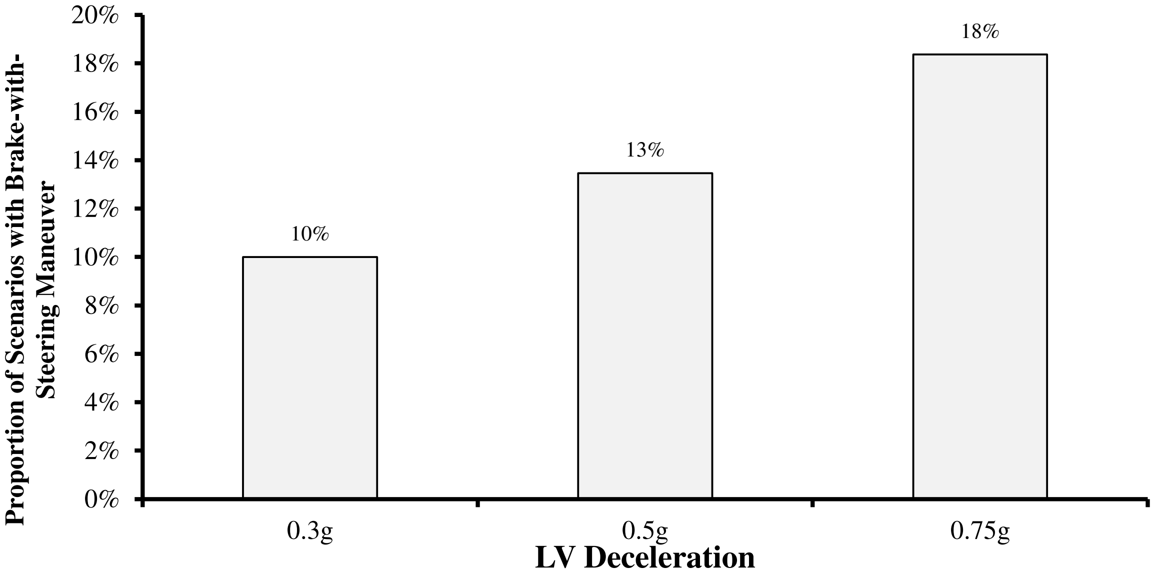


Fig. 11 Proportion of scenarios with brake-with-steering maneuver under different LV decelerations

4.2. Perception Response Time

As described by McGehee et al. (2002), drivers' perception response time is a complex sequential process that begins when drivers identify a hazard, decide the likely action of the threatening vehicle and select an action, and ends with execution of a maneuver (steering, braking, or both). In this study, the obtained mean PRTs for different combinations of initial headway and LV deceleration ranged from 1.34 (S/0.75g condition) to 3.01 sec (L/0.3g condition).

TABLE 11 presents a summary of PRTs reported by previous studies. All of the reviewed studies used LV deceleration as an emergency scenario except McGehee et al. (2002), who used stationary LV scenarios. The studies are sorted by the initial headway values. As can be seen, PRT is near 1 sec when the initial headway is around 1.5 sec, but PRT increases, sometimes dramatically, at greater headways.

Some may argue that as initial headway and LV deceleration varied, drivers' reaction time did not change, and instead, drivers might intentionally delay braking until the distance or headway or TTC reached a somehow constant value. If this were the case, the distance or headway or TTC at SV brake onset should be constant regardless of variation in the initial headway or LV deceleration. To examine this possibility, analyses on the distance, headway, and TTC at SV brake onset were conducted. These analyses showed that initial headway had a significant main effect on both distance ($F_{[2,100]}$=102.59, p<0.0001) and headway ($F_{[2,100]}$=102.00, p<0.0001) at SV brake onset, and that LV deceleration had a significant main effect on TTC at SV brake onset ($F_{[2,100]}$=36.44, p<0.0001). This shows that drivers did not intentionally delay braking until the distance or headway or TTC reached a constant value.

TABLE 11 Summary of PRT and throttle release time in current and previous studies

Study	Headway (sec)	LV deceleration (g)	PRT (sec)	Throttle release time (sec)
Current study	**<1.0**	**0.75**	**1.34**	**0.61**
Jamson et al. (2008)	1~3	0.4	1.20	
Ohlhauser et al. (2011)	1.5	1.00	1.10~1.30	
Abe and Richardson (2006)	1.7	0.80	0.94~1.14	0.65~0.82
Abe and Richardson (2004)	2.0	0.90	1.20	0.80
Abe and Richardson (2006)	2.2	0.80	0.92~1.20	0.62~0.81
Current study	**1.5~2.5**	**0.75**	**1.94**	**1.00**
Lee et al. (2002)	1.7~2.5	0.40~0.55	2.69	2.04
Lee et al. (1997)	2.7	0.85	2.98*	2.48
Lee et al (1997)	3.2	0.85	2.70*	2.20
McGehee et al. (2002)	3.2		2.53	

**Because PRT was analyzed in Lee et al. (1997) but not reported, PRTs of Lee et al. (1997) were estimated by adding an assumed 0.5 sec throttle to brake transition time to throttle release time. According to results of the Lee et al. (1997), throttle to brake transition time was not affected by situational urgency and had a value around 0.5 sec.*

All of these studies were simulator studies and all of these studies used LV decelerating as an emergency scenario except McGehee et al. (2002), who used stationary LV scenarios.

PRTs and throttle release times of Abe and Richardson (2004) and Jamson et al. (2008) were estimated from figures because no explicit values were reported.

Throttle release time = $T_{Init} + T_{Final}$.

This study also found an effect of exposure on PRT. Specifically, drivers responded significantly more slowly in the first trial than in the latter trials, with an average PRT difference of 0.67 sec. This is consistent with the finding of Lee et al. (2002) in which the reaction time for throttle release decreased from 2.11 sec in the first trial to 1.67 sec in the second trial. These findings provide further support to the viewpoint of Green (2002) that PRT is affected by driver expectation. Meanwhile, this significant change (0.67 sec) in PRT after the first trial may also indicate that the practice drive was not sufficient for drivers to be familiar with the simulated driving environment or the vehicle controls (brake pedal, accelerator pedal, etc.) of simulator car.

4.3.Pre-brake Reaction Sequence

Driver's pre-brake reaction sequence is comprised of T_{Init}, T_{Final}, and $T_{brake.}$ The obtained T_{Init}, ranged from 0.62 to 1.62 sec under different initial headways. This large range can also be seen in TABLE 11. However, neither initial headway nor LV deceleration had a significant effect on T_{Final} or T_{brake}, indicating T_{Final} and T_{brake} are two largely fixed components of the pre-brake reaction sequence. This supports the opinion of Young and Stanton (2007) that as drivers have increased amounts of time available to react to the braking of the lead vehicle, they devote this extra time to cognitive, rather than physical, activities.

4.4.Post-brake Reaction Sequence

The post-brake reaction sequence, which is comprised of $T_{25\%Brake}$, $T_{50\%Brake}$, and $T_{MaxBrake}$, examined the delay from the driver's initial brake application to various degrees of brake pedal pressure. The results showed that these delays varied significantly under different levels of situational urgency. The obtained mean $T_{MaxBrake}$ for different combinations of initial headway and LV deceleration ranged from 0.92 to 4.21 sec. To further examine the cause of this variation, profiles of brake pedal force under L/0.3g and S/0.75g conditions were mapped to a 0 to 1 timeline and compared, as shown in Fig. 12. The solid line shows brake pedal profiles under low urgency condition (L/0.3g), and the dashed line show brake pedal profiles under high urgency condition (S/0.75g).

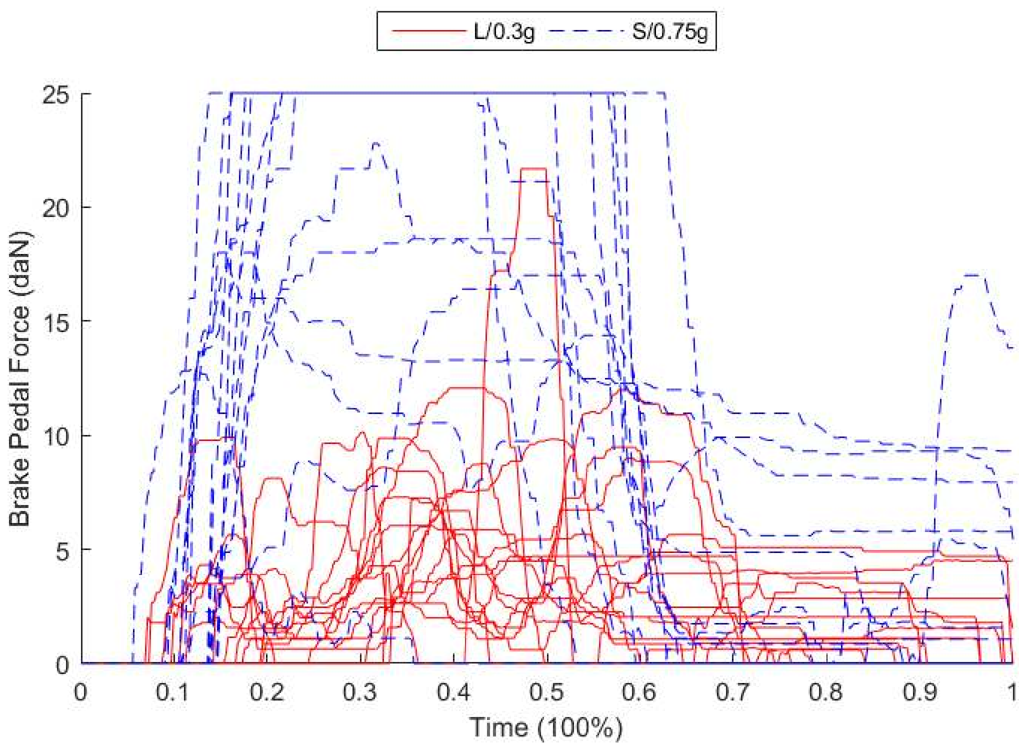


Fig. 12 Plots of brake pedal force profiles under L/0.3g and S/0.75g conditions

Note: The number of scenarios under L/0.3g and S/0.75g conditions were 15 and 14 respectively, and all the observations were used to produce the current figure.
Time point 0 stands for LV brake onset for each rear-end scenario, and time point 1 stands for 5 seconds after SV stopping onset or crash onset.

As can be seen in the figure, at low levels of situational urgency (e.g., L/0.3g condition), drivers typically exhibit multi-stage braking behavior in response to potential rear-end collisions. Namely, drivers initially applied the brake moderately and then held the brake pedal momentarily at a moderate application level. If the driver then perceived that the threat could not be avoided by moderate braking, he then changed to full brake application (Every et al., 2014). This multi-stage braking behavior caused drivers to take much longer time to reach full emergency braking.

Similar multi-stage braking phenomena have been seen among truck drivers (Every et al., 2014). According to Prynne and Martin (1995), this behavior pattern is a result of humans not having instinctive reactions to situations of vehicle emergency. They regarded the first stage as an initial reaction to the given emergency situation, and the following stages as a result of the driver's decision on a course of action.

4.5.Brake Intensity

Unlike the time-based metrics, maximum brake pressure measures the force a subject exerts on the brake pedal. Together with peak deceleration, it measures the intensity of drivers' braking. The obtained mean of peak deceleration ranged from 0.7 to 1g. This range is compatible with a previous study by Mazzae et al. (2003) that recorded a mean peak deceleration of 0.72 g in their test-track study. Kiefer et al. (1999), also using a test track, found maximum decelerations of 0.9 g when participants were instructed to brake at the last second in response to lead vehicle decelerations. Results showed the maximum brake pressure and peak deceleration depended on LV deceleration. As can be seen from Fig. 12, drivers brake harder at higher LV deceleration rates.

5. Summary and Implications

A high fidelity driving simulator was used to test drivers' collision avoidance behaviors under different initial headways and different lead vehicle deceleration rates. Drivers' braking and steering decisions, perception response times (PRT), throttle release response times, throttle to brake transition times, brake delays, maximum brake pedal pressures and peak decelerations were assessed. The major findings are summarized below:

1) Drivers' response times and brake behaviors varied under different levels of rear-end situational urgency. Generally, as situational urgency increased, drivers released the accelerator faster, braked to full braking more quickly, and braked harder;

2) PRT was near 1 sec when the initial headway was around 1.5 sec, but PRT increased, sometimes dramatically, at larger headways;

3) Transition time between initial throttle release and brake initiation was a fixed component (about 0.8 sec) of the pre-brake reaction sequence, which was not affected by initial headway or LV deceleration rate;

4) There was a at least 0.92 sec driver-related delay between brake initiation and full braking;

5) At low situational urgency, drivers exhibited multi-stage braking behavior in response to potential frontal crash conflicts, which led to longer delay from brake initiation to full emergency braking;

6) Drivers modulated their braking intensities based on how fast the two vehicles were closing (reflected by LV deceleration rate), and braked harder when LV deceleration rate increased;

7) Exposure affected drivers' PRT. Specifically, drivers averagely responded 0.67 sec more slowly in the first trial than in the latter trials.

Driving simulators have been shown to be a reliable source of driver behavior data under rear-end collision scenarios (Lee et al., 2002; McGehee et al., 2002). One common issue concerning driving simulators has been the validity of their results. The validity of the current study is supported by the following: 1) the Tongji University driving simulator passed an overall capabilities test on several dimensions that measured validity; 2) the maximum SV decelerations during rear-end scenarios ranged from 0.70 g to 1 g, with the mean value of 0.89 g, and this is consistent with previous test-track studies (0.72g) (Mazzae et al., 2003); 3) subjective evaluations of realism obtained from participants supported the validity of the driving simulator.

Although this study provided information on drivers' collision avoidance behaviors under different levels of situational urgency, two limitations associated with the current study could be addressed in future research. Effects of driver age, gender, and driving experience on drivers' collision avoidance behaviors were not explored, and similar to the Kiefer et al. CAMP study (1999), traffic was not present on the adjacent lane of the SV in the current study. Given that in actual driving situations, drivers need to monitor nearby vehicles, it is likely that drivers' response times would be longer in real world. And also, an issue related to the experimental design could be handled more carefully in future studies— during the 30 minute test phase, 2 cases were randomly introduced where LV slowed down but with small deceleration rates of 0.02g to 0.1g. These cases can reduce the predictability of LV stops, but may also misplace the trust of participants for the actual LV stops.

An FCW is an on-board electronic safety device that has the potential to warn the driver of the host vehicle of an impending collision with preceding traffic. These systems use a forward-looking radar that continuously monitors traffic obstacles in front of the host vehicle and warn the driver when a risk of collision is imminent (Jamson et al., 2008). The findings of this study have several implications for FCW development:

1) FCW systems may benefit from considering the effects of situational urgency on drivers' response times and braking intensity. The timing of a FCW alarm is fundamental to the functionality of the complete system. Late warnings, that allow insufficient time for a driver to react to an unfolding scenario, result in more collisions than no system at all. On the other hand, the earlier a warning occurs, the more likely it is to be interpreted as a false alarm, which in turn leads to a reduction in drivers' future system use (Jamson et al., 2008). FCW systems apply assumptions describing driver response time and braking intensity to determine when an alert should be presented (McLaughlin, 2007). Results of this study suggest that situational urgency affects both drivers' response times and their braking intensity, and these effects should be considered when developing FCW timing algorithms, e.g., Wang et al. (2016);
2) It has traditionally been assumed that full braking occurs upon completion of the mechanical brake delay (Ising et al., 2012). The findings of this study suggest that at least 0.92 sec driver-related delay between brake initiation and full braking should be noticed;
3) Given the observation that drivers do not always apply full braking pressure, FCW warnings might be followed by braking assist measures that automatically increase the vehicle deceleration in collision imminent situations.

6. ACKNOWLEDGEMENT

This study was supported by the Chinese National Science Foundation (51522810).

7. REFERENCES

[1] Abe, G., Richardson, J., 2004. The effect of alarm timing on driver behaviour: an investigation of differences in driver trust and response to alarms according to alarm timing. Transportation Research Part F: Traffic Psychology and Behaviour 7(4), 307-322.

[2] Abe, G., Richardson, J., 2006. Alert timing, trust and driver expectation for forward collision warning systems. Applied Ergonomics 37(5), 577-586.

[3] Adams, L. D., 1994. Review of the literature on obstacle avoidance maneuvers: braking versus steering (No. UMTRI-94-19).

[4] Aust, M. L., Engström, J., Viström, M., 2013. Effects of forward collision warning and repeated event exposure on emergency braking. Transportation Research Part F: Traffic Psychology and Behaviour, 18, 34-46.

[5] Boyle, L.N., Lee, J.D., 2010. Using driving simulators to assess driving safety. Accident Analysis and Prevention 42(1), 785-787.

[6] Curry, R.C., Greenberg, J.A., Kiefer, R.J., 2005. NADS versus CAMP closed-course comparison examining "last-second" braking and steering maneuvers under various

kinematic conditions. Publication DOT HS 809 925, NHTSA, U.S. DOT.
[7] Engström, J., 2010. Scenario criticality determines the effects of working memory load on brake response time. In J. Krems, T. Petzoldt, & M. Henning (Eds.), Proceedings of the European conference on human centered design for intelligent transport systems (HUMANIST) (pp. 25–36). Lyon, France.
[8] Every, J. L., Salaani, M. K., Barickman, F. S., Elsasser, D. H., Guenther, D. A., Heydinger, G. J., Rao, S. J., 2014. Braking behavior of truck drivers in crash imminent scenarios. SAE International Journal of Commercial Vehicles 7(2014-01-2380), 487-499.
[9] Fitch, G. M., Blanco, M., Morgan, J. F., & Wharton, A. E., 2010. Driver braking performance to surprise and expected events. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting 54(24), 2075-2080. SAGE Publications.
[10] German Federal Statistical Office, 2009. Verkehrsunfälle. Fachserie 8, Reihe 7.
[11] Green, M., 2000. “How long does it take to stop?” methodological analysis of driver perception-brake times. Transportation Human Factors 2(3), 195-216.Hirose, T., Taniguchi, T., Hatano, T., Takahashi, K., Tanaka, N., 2008. A study on the effect of brake assist systems (BAS) (No. 2008-01-0824). SAE Technical Paper.
[12] Hulst, M. V. D., 1999. Anticipation and the adaptive control of safety margins in driving. Ergonomics 42(2), 336-345.
[13] Ising, K. W., Droll, J. A., Kroeker, S. G., D’Addario, P. M., Goulet, J. F., 2012. Driver-related delay in emergency braking response to a laterally incurring hazard. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting 56(1), 705-709. Sage Publications.
[14] Jamson, A. H., Lai, F. C., Carsten, O. M., 2008. Potential benefits of an adaptive forward collision warning system. Transportation Research Part C: Emerging Technologies 16(4), 471-484.
[15] Kassaagi, M., BRISSART, G., POPIEUL, J. C., 2003, May. A study on driver behavior during braking on open road. In 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Nagoya (Japan).
[16] Kiefer, R.J., LeBlanc, D.J., Palmer, M., Salinger, J., Deering, R., Shulman, M., 1999. Development and validation of functional definitions and evaluation procedures for collision warning/avoidance systems. Publication DOT HS 808 964, NHTSA, U.S. DOT.
[17] Kiesewetter, W., Klinkner, W., Reichelt, W., Steiner, M., 1999. The New Brake Assist of Mercedes-Benz Active Driver Support in Emergency Braking Situations. Vehicle Performance: Understanding Human Monitoring and Assessment, 67-83.
[18] Lee, J., McGehee, D.V., Brown, T.L., Reyes, M.L., 2002. Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. Human Factors: The Journal of the Human Factors and Ergonomics Society 44(2), 314–334.

[19] Lee, J., McGehee, V.D., Dingus, T.A., Wilson T., 1997. Collision avoidance behavior of unalerted drivers using a front-to-rear-end collision warning display on the iowa driving simulator. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1573, Transportation Research Record of National Academies, Washington, D.C., pp.1-7.

[20] Liebermann, D. G., Ben-David, G., Schweitzer, N., Apter, Y., Parush, A., 1995. A field study on braking responses during driving. I. Triggering and modulation. Ergonomics 38(9), 1894-1902.

[21] Limpert, R., Gamero, F. E., 1974. The accident avoidance potential of the motor vehicle: accident data, vehicle handling and safety standards. In *Proceedings of the Third International Congress on Automotive Safety* (Vol. 11).

[22] Mazzae, E., Barickman, F., Forkenbrock, G., Baldwin, G., 2003. NHTSA light vehicle antilock brake systems research program task 5.2/5.3: Test track examination of drivers' collision avoidance behavior using conventional and antilock brakes. Washington, DC: National Highway Transportation Safety Administration.

[23] McGehee, D.V., Brown, T.L., Lee, J.D., Wilson, T.B., 2002. Effect of warning timing on collision avoidance behavior in a stationary lead vehicle scenario. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1803, Transportation Research Record of National Academies, Washington, D.C., pp.1-6.

[24] McLaughlin, S. B.,2007. Analytic assessment of collision avoidance systems and driver dynamic performance in rear-end crashes and near-crashes.

[25] Muttart, J. W.,2005. Estimating driver response times.

[26] Ohlhauser, A.D., Milloy, S., Caird, J.K., 2011. Driver responses to motorcycle and lead vehicle braking events: The Effects of motorcycling experience and novice versus experienced drivers. Transportation Research Part F: Traffic Psychology and Behaviour 41(6), 472-483.

[27] OKTAL, SCANeR™ Studio software. http://www.scanersimulation.com, Accessed Oct.19, 2015.

[28] Perron, T., Kassaagi, M., Brissart, G., 2001. Active safety experiments with common drivers for the specification of active safety systems. In 17th International Technical Conference on Enhanced Safety of Vehicles, Amsterdam.(Paper Number 427) Retrieved from http://www-nrd. nhtsa. dot. gov/database/nrd-01/esv/asp/esvpdf. asp.

[29] Prynne, K., Martin, P., 1995. Braking behaviour in emergencies (No. 950969). SAE Technical Paper.

[30] Roody, S. S., 2011. Modeling Drivers' behavior during panic braking for brake assist application, using neural networks and logistic regression and a comparison (No. 2011-01-2384). SAE Technical Paper.

[31] Schweitzer, N., Apter, Y., Ben-David, G., Liebermann, D. G., Parush, A., 1995. A field

study on braking responses during driving. II. Minimum driver braking times. Ergonomics 38(9), 1903-1910.
[32] Sohn, S. Y., Stepleman, R., 1998. Meta-analysis on total braking time. Ergonomics 41(8), 1129-1140.
[33] Summala, H., 2000. Brake reaction times and driver behavior analysis. Transportation Human Factors 2(3), 217-226.
[34] Summala, H., Lamble, D., Laakso, M., 1998. Driving experience and perception of the lead car's braking when looking at in-car targets. Accident Analysis & Prevention 30(4), 401-407.
[35] Traffic Safety Facts 2013, 2013. Publication DOT HS 812 139, NHTSA, U.S. DOT.
[36] Tukey, J. W., 1949. Comparing individual means in the analysis of variance. Biometrics 5 (2), 99-114.
[37] Wang, X., Chen, X., and Deng, B. 2011. Shanghai 2020 driving scenario models and traffic accident models development. General Motor, Shanghai, Unpublished report.
[38] Wang X., Chen M., Zhu M., Tremont P., 2016. Development of a kinematic-based forward collision warning algorithm using an advanced driving simulator. IEEE Transactions on Intelligent Transportation Systems PP (99), 1-9, in press.
[39] Watanabe, Y., Ito, S., 2007. Influence of vehicle properties and human attributes on neck injuries in rear-end collisions. Paper No. 07-0160. 20th Int. ESV Conf.
[40] Winsum, W. V., Heino, A., 1996. Choice of time-headway in car-following and the role of time-to-collision information in braking. Ergonomics 39(4), 579-592.
[41] Yoshida, H., Sugitani, T., Ohta, M., Kizaki, J., Yamamotoz, A., Shirai, K., 1998. Development of the brake assist system (No. 980601). SAE Technical Paper.
[42] Young, M. S., Stanton, N. A., 2007. Back to the future: Brake reaction times for manual and automated vehicles. Ergonomics 50(1), 46-58.