

## Research Article

# Effectiveness of Flashing Brake and Hazard Systems in Avoiding Rear-End Crashes

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Three experiments were conducted to examine the effectiveness of two forward crash warning systems, a flashing brake system and a flashing hazard system, using an advanced driving simulator. In Experiment 1, 20 subjects followed a lead vehicle with a desired time gap and braked when necessary. Results showed that time gap, velocity, and deceleration of the lead vehicle all significantly affected drivers' brake response times. In Experiment 2, six brake response times to a sudden lead vehicle deceleration (0.6 g at 80 km/h) were measured for six time gaps. Results showed that flashing brake system and flashing hazard system reduced drivers' brake response times by 0.14~0.62 s and 0.03~0.95 s, respectively, in the various situations tested. The effects of flashing color and illuminated size on drivers' brake response times were examined in Experiment 3. Results showed that flashing amber lamps reduced drivers' brake response times significantly by 0.11 s (10%) on average compared with red lamps. These findings demonstrate the effectiveness of both flashing systems in reducing drivers' brake response times in urgent situations and may warrant further consideration by manufacturers.

## 1. Introduction

Rear-end crashes, accounted for 32.2% of all road crashes, lead to 1694 deaths and 476,000 injuries in the US in 2010 [1]. In the same year in China, 2691 people died because of highway rear-end crashes which account for 40.4% of all highway crashes [2]. Rumar [3] established that delayed detection of other road users caused by inattention was a primary contributing factor for these crashes in 1990. As in-vehicle systems proliferate, the problem of driver inattention/distraction will become worse. Consequently, many warning and crash mitigation systems are being developed to reduce the frequency and severity of rear-end crashes [4, 5]. One purpose of such systems is to alert drivers of the imminent danger so that they can make evasive maneuvers to avoid a crash [6].

There have been many studies that have examined how to warn drivers of impending rear-end crashes. Jeong and Green [7] summarized 17 studies covering 27 experiments concerning human factors and in-vehicle forward collision warnings. This review showed that warning systems (visual,

audio, and/or tactile) led to fewer crashes and shorter brake response times. However, none of these studies considered seat belt pretensioner activation which is an effective way to reduce crashes [8–10]. This review also reported that for audio warnings, intensities 4–10 dB above the background level were the most effective in reducing driver's brake response time.

In addition, there has been considerable research on external warnings, primarily on brake lights, with primary topics being how to make them more conspicuous (by altering their location, size, luminance, etc.) and how to provide additional cues (especially, the deceleration of the lead vehicle, e.g., by flashing the brake light). Brake light design has been the source of numerous patents. For example, Tewari [11] invented a method to modulate brake lights intensity and flash rate based on the vehicle deceleration, and Kim [12] invented an automatic flashing brake lights system that varied the flashing frequency based upon the braking force a driver applied.

One idea that has received considerable attention was to provide an additional brake lamp in a location closer

to the line of sight—the Center High Mounted Stop Lamp (CHMSL). Initial research on CHMSL has indicated that it should reduce rear-end crashes in several situations [13–16]. Since model year 1986, all passenger cars in the United States have to be equipped with CHMSL, as required by the Federal Motor Vehicle Safety Standard 108 [17]. European requirements for a CHMSL were also added to ECE R7 [18] in the early 1990s. However, a CHMSL seems to be more effective in some simpler crash scenes and less effective in complex situations [16]. In terms of the long-term effectiveness of CHMSL, Kahane and Hertz [16] found that it reduced the number of rear-end crashes by 4.3 percent, half of the number in the earlier years. Sivak et al. [13] conducted three experiments on the effectiveness of CHMSL, finding that it did not have significant effects on drivers' brake response times under medium-speed/long-following-distance conditions.

Altering the lighting pattern of brake lamps to increase their salience has been the topic of considerable research. For example, Shinar [19, 20] proposed brake lights to be illuminated when driver released the accelerator pedal. Gail et al. [21] summarized the literature on brake force display indicating braking intensity by means of increase in luminance and size. Wierwille et al. [22] evaluated two flashing prototypes of enhanced brake systems. Li and Milgram [23] showed the effectiveness of optical looming cues of lead vehicle. Isler and Starkey [24] tested the effect of rear hazard lights which could be activated when deceleration exceeded preset thresholds. A rear window notification display changing with acceleration and time headway was evaluated by Saffarian et al. [25] in 2013. Most of these various brake signal modification ideas stemmed from a landmark field study conducted in 1974 using a fleet of taxi cabs [26]. In this study, a deceleration warning light system mounted on the rear of a vehicle was activated by the use of brake pedal and changed with deceleration rate (g).

Among the ideas, flashing rear lamps have been promising signals for use in enhanced brake system applications, especially when the lamps appear just in the periphery of driver's visual field. Neurauter et al. [27] measured the time a driver took to look up from a navigation system display to outboard lamps flashing alternatively with CHMSL at 4.75 Hz and found that response time was reduced by 1.82 s (30%) compared with the conventional ones. Improvements of response times by flashing can also be found in [21, 28]. However, in a static test in which a manually made plywood board vehicle was equipped with various light signals, there was no significant difference about drivers' brake response times when the signals flashed at either 1.5 Hz or 5 Hz, probably because of the unusual experimental setup [29]. Improvements of response times with flashing rear lamps were also observed for motorcycles, both in laboratory and on-road test [30]. A reduction of 80 ms (10%) was observed for the modified motorcycle brake lamps flashing at 1.5 Hz than for the conventional (nonflashing) ones. To determine the optimum flash frequency for use as an imminent warning signal, a flashing frequency of approximately 4 Hz has proven to be the optimum [31, 32], which was supported by the expert

subjective evaluation in a study conducted by Wierwille et al. [22].

The pattern of brake lamp illumination has also received attention. Li and Milgram [23] proposed that exaggerating the apparent rate of optical looming, whenever a lead vehicle brakes very hard or when forward distance gap is very short, can provide the following driver with an intuitive illusion that the lead vehicle is approaching more rapidly, causing the driver to react more quickly. The results of the experiments showed that drivers braked 140 ms sooner or 60 ms later when seeing the expanding (0.4 s ahead) or contracting (0.4 s behind) brake lights at night, respectively, in comparison with the conventional ones. A similar graded deceleration display was designed to replace the rear center high mounted stop lamp in vehicles [33]. Results entailed that the maximum depression of the brake pedal was enhanced by 8% when the graded display was used, and the minimum following distance was increased by 4.6 m (15%), compared with the binary system.

Keep in mind that systems that use information on range rate to the lead vehicle need to have a radar or LIDAR or camera based system to detect lead vehicles and compute their range rates. These technologies have only become available in the last few years. Further, in the ongoing Safety Pilot model deployment [34], being conducted by University of Michigan Transportation Research Institute (UMTRI), data on the distance between vehicles is being determined using vehicle-to-vehicle communications. Approximately 2,850 vehicles will participate in the testing phase.

To date, there have been many promising evaluations of enhanced brake systems to reduce the likelihood of rear-end crashes. However, except for the CHMSL, none of these systems have been adopted as required equipment for passenger cars. This may be because their performance benefits are small. Drivers' brake response times to enhanced brake systems in most of previous studies were usually measured when all the vehicles were static, or when a driver followed the lead vehicle with a fixed distance at a certain speed, or when various scenarios were averaged over for a mean value. Unknown is how drivers' brake response times would change as a function of time gap for various enhanced emergency braking systems.

As shown in Figure 1, two enhanced flashing systems, flashing brake system and flashing hazard system, were proposed to be analyzed in this study. Both systems satisfy the legal requirements in regulations and standards in ECE R48 [35]. For the flashing brake system, both the stop lamps and CHMSL were illuminated when lead vehicle started to decelerate. When that vehicle's deceleration first exceeded 0.6 g, both sets of lamps would be triggered to flash at 3.6 Hz until the deceleration of lead vehicle was less than 0.4 g. The stop lamps and CHMSL functioned in the same way for the conventional brake system and flashing hazard system. However, hazard lamps could be triggered to flash at 3.6 Hz in flashing hazard system. The on and off times for flashing in hazard system were the same with that in the flashing brake system. The flash duty cycle of both systems was half on and half off. The main differences between these two flashing systems were that both stop lamps and CHMSL

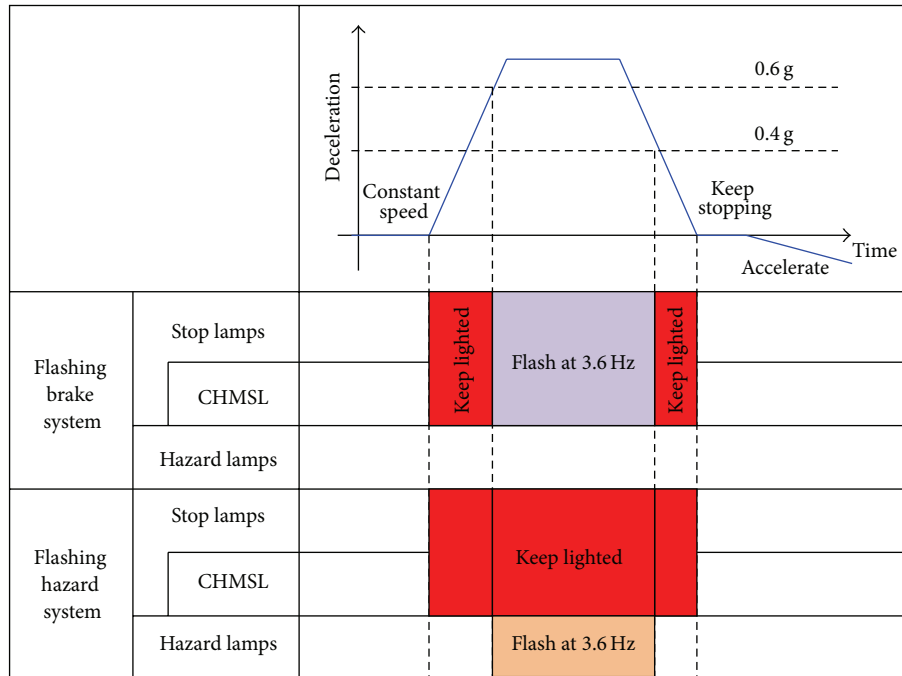


FIGURE 1: The timing of flashing brake system and flashing hazard system.

could be triggered to flash in flashing brake system, while, in flashing hazard system, both stop lamps and CHMSL would remain lighted and hazard lamps could be triggered to flash when a vehicle decelerated.

In this study, drivers' brake response times were analyzed to quantify the effectiveness of three brake systems, conventional braking system, flashing brake system, and flashing hazard system, in emergency situations using a driving simulator. By providing more information than the conventional braking system, both flashing systems were expected to reduce drivers' brake response times.

Specifically, three questions were addressed in this study.

- (1) Which is the most influential factor (time gap, velocity, deceleration, or brake system type) on drivers' brake response times?
- (2) How do both flashing systems and the conventional system affect drivers' brake response times as a function of time gap?
- (3) How do colors (red and amber) and illuminated sizes (large and small) affect drivers' brake response times?

Three experiments were carried out to answer these questions. Experiment 1 used an orthogonal experiment design to determine which factor (time gap, velocity, deceleration, or brake system type) was the most influential on drivers' brake response times. Experiment 2 examined the effect of the time gap (1.0 to 3.5 s with a step of 0.5 s) on drivers' brake response times to all the three brake systems. Experiment 3 examined the contributing factors, flashing color, and illuminated size, to both flashing systems.

## 2. Experiment 1: Relative Effect of the Time Gap, Deceleration, Velocity, and Brake System Type

### 2.1. Method

**2.1.1. Participants.** Twenty (17 men, 3 women) licensed drivers participated in this experiment. Their age ranged from 22 to 33 years old ( $M = 26$ ,  $SD = 3$ ). On average, they had 4 years driving experience ( $SD = 3$ ). All the subjects in all three experiments did not have any disabilities that would degrade their driving performance.

**2.1.2. Apparatus.** To evaluate the effectiveness of systems using a driving simulator, the force feedback of the brake pedal, the representation of the relative speed, and the distance to the lead vehicle in the simulator must be similar to that of an actual vehicle [36]. The advanced simulation system used in all three experiments in this paper is a 6-degree-of-freedom, moving base driving simulator to make driving experience as realistic as possible.

The driving scenario is projected onto three front screens providing a 220° forward field of view (with embedded rearview and side mirrors), and two rear screens providing 55° rear field of view (Figure 2). The audio system provides simulated engine, road, and traffic sounds. The motion system has a simulated angular (roll, yaw, pitch) and longitudinal movement of  $\pm 15^\circ$  and  $\pm 0.4$  m, respectively. The software can simulate various traffic scenarios, including different vehicle types and various road types. Spatial parameters of vehicles and driving performance data for each subject



FIGURE 2: Overview of the driving simulator.

TABLE 1: Levels of impact factors.

Factors	Level.1	Level.2	Level.3
A: velocity (km/h)	60	80	100
B: time gap (s)	1.0	2.0	3.0
C: deceleration (g)	0.4	0.6	0.8
D: brake system type	Conventional	Flashing brake	Flashing hazard

(speed, acceleration/deceleration, steering angle, etc.) can all be recorded at 60 Hz.

**2.1.3. Procedure.** Drivers' brake response times were assumed to be affected by the time gap (as defined in SAE draft Recommended Practice J2944 [37]), velocity, deceleration of lead vehicle, and brake system type. To determine which factor had the greatest influence on drivers' brake response times, an orthogonal experiment design method was adopted. As shown in Table 1, all the four factors are in three levels. Using  $L(3^4)$  experiment design method, nine emergency situations, counterbalanced across subjects, need to be tested (see Table 2). A within subject design method was adopted in all the three experiments in this study.

Besides the nine emergency situations, various following situations, including accelerating/decelerating, overtaking, and pulling over, were created to make the driving experience as real as possible and avoid subjects learning the sequence of situations. The procedure for scheduling the scenarios is shown in Figure 3.

In this study, subjects were instructed to follow a specific lead vehicle with a desired time gap as steadily as possible and to brake when necessary based on their own driving experience. As illustrated in Figure 4, the desired time gap was indicated on a simulated head-up display projected onto the front screen. A left-right movable arrow showed whether the current following distance was too near or too far. Each participant drove through all the nine scenarios once. The emergency scenario occurred once every 5 to 10 minutes according to their following stability with the lead vehicle.

The desired time gap was indicated by dark blue color in the middle of the color bar. The moving arrow gave the current following time gap and subjects adjusted their speed to keep the arrow in the middle of the color bar. When the following time gap was within the desired range (desired

time gap  $\times (1 \pm 5\%)$ ), a timer was started, which resets to zero when the gap was not within the desired range. When a subject followed the lead vehicle within the desired time gap region for more than 5 seconds consecutively, the lead vehicle braked. At that point, the timer stopped and the arrow stayed where it was the last moment before lead vehicle started to brake to avoid the indication of the emergency by the quick movement of the arrow.

**2.1.4. Data Analysis.** Statistical software PASW Statistics 18 was used to analyze subjects' brake response times to various emergency situations. Brake response time here is defined as the time from the activation of lead vehicle's brake light until first foot contact with the brake pedal (per SAE draft Recommended Practice J2944 [37]).

**2.2. Results.** Subjects' brake response times as a function of velocity, time gap, deceleration of the lead vehicle, and brake system type were shown in Figure 5. Brake response time was significantly affected by velocity ( $F(2, 171) = 8.40$ ,  $p < 0.001$ ), time gap ( $F(2, 171) = 42.03$ ,  $p < 0.001$ ), and deceleration of the lead vehicle ( $F(2, 171) = 8.41$ ,  $p < 0.001$ ). No significant effect of brake system type on brake response time was found ( $F(2, 171) = 2.99$ ,  $p = 0.053$ ). As illustrated in Figure 5, increased velocity, larger following time gap, and greater deceleration of the lead vehicle could lead to shorter brake response times.

**2.3. Discussion.** For a fixed speed, a briefer time gap corresponds to a shorter following distance (time gap = following distance/speed). The closer the lead vehicle, the larger its visual angle, making it easier to recognize that the lead vehicle is braking. The potential danger drives subjects to pay more attention to the lead vehicle to avoid a crash once something occurs, leading to a faster response in shorter following time gap situations.

As illustrated in Figure 5, increased velocity and greater deceleration could lead to shorter brake response times. Similar results were found in other studies. Probst [38] found that the average times subjects spent to detect changes in headway were 0.96 and 2.06 s when following with distances of 20 m at 50 m/h and 40 m at 80 km/h, respectively. They would not react to a stimuli as fast as when they drive at a lower speed. Brown et al. [39] showed that relative velocity at collision increased with the deceleration of the lead vehicle, probably because it took more time for drivers to react to the imminent dangers at a higher speed.

If a driver's brake response time can be reduced by about 0.2 s, the stopping distance can be reduced by approximately 4.4 m when the initial velocity is 80 km/h and the deceleration is 0.8 g. This is a practically significant difference. In a study conducted by Wierwille et al. [22], an enhanced rear lighting system called ImpAltPr (improved alternating pair, flashing at 4.0 Hz) improved drivers' brake reaction times by 0.25 s (15%), similar with the results found in this experiment. Also, Gail et al. [21] found that brake lights with flashing hazard lights could reduce response times by 0.23 s (13%) compared with the conventional brake system. Comparatively, a red



TABLE 2: Scenarios need to be tested.

Combinations	Velocity (km/h)	Time gap (s)	Deceleration (g)	Brake system type
A1B1C1D1	60	1.0	0.4	Conventional
A1B2C2D2	60	2.0	0.6	Flashing brake
A1B3C3D3	60	3.0	0.8	Flashing hazard
A2B1C2D3	80	1.0	0.6	Flashing hazard
A2B2C3D1	80	2.0	0.8	Conventional
A2B3C1D2	80	3.0	0.4	Flashing brake
A3B1C3D2	100	1.0	0.8	Flashing brake
A3B2C1D3	100	2.0	0.4	Flashing hazard
A3B3C2D1	100	3.0	0.6	Conventional

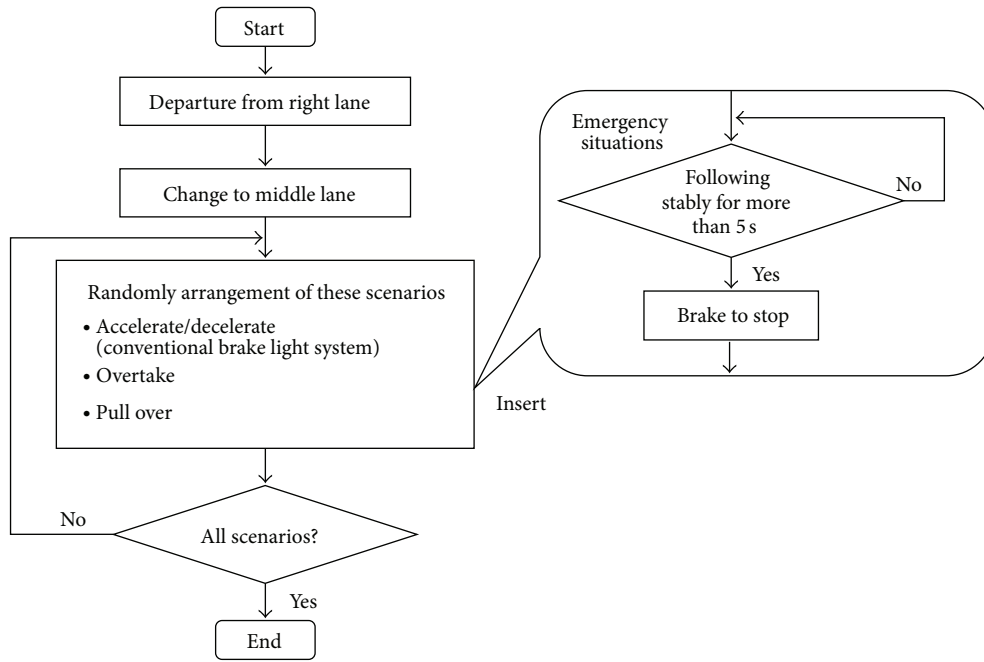


FIGURE 3: The procedure for scheduling the scenarios.

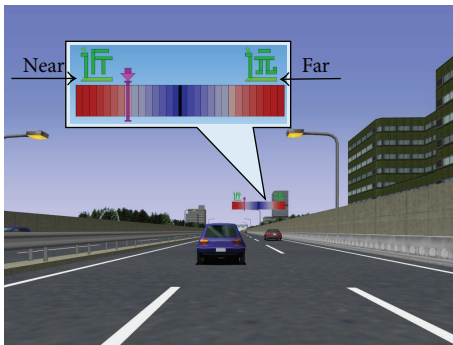


FIGURE 4: Following scenario.

brake lights flashing at 20 Hz only showed 14 ms (4%) and 29 ms (7%) improvement on response times in two simulated driving tasks [28]. However, no significant effects of brake system types on response times were found in this

experiment. To analyze how do these brake systems function in specific driving situations, time gap, the most influential factor, was examined further.

### 3. Experiment 2: How Do Drivers' Brake Response Times to Various Braking Systems Vary as a Function of Time Gap?

#### 3.1. Method

**3.1.1. Participants.** Twenty-one male subjects participated in this experiment. The subjects ranged in age from 21 to 49 years ( $M = 35$ ,  $SD = 9$ ). Their driving experience varied from 3 to 15 years ( $M = 8$ ,  $SD = 5$ ).

**3.1.2. Procedure.** Six time gaps (1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 s) were tested. Deceleration of the lead vehicle was 0.6 g and the driving speed was 80 km/h. Each of the 6 time gaps was

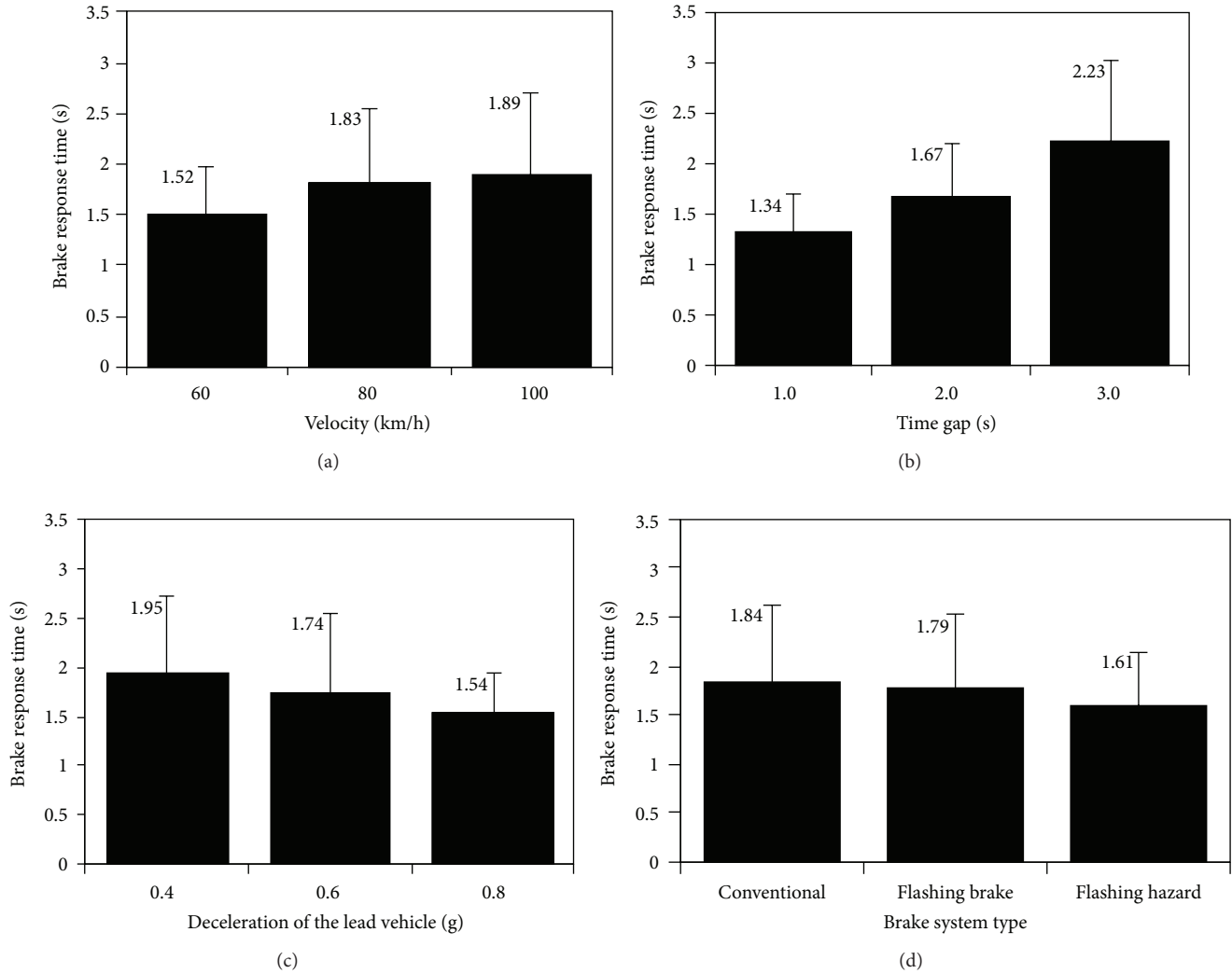


FIGURE 5: Subjects' brake response times as a function of velocity (a), time gap (b), deceleration of the lead vehicle (c), and brake system type (d).

presented 3 times (one time for each brake system), for a total of 18 trials. The 18 trials were split into two groups of 9 and counterbalanced across subjects. Eighteen nonemergency situations (acceleration, slight deceleration, overtaking) were also included to simulate real road driving experience. Before the first block, in between the first and second block, and after the second block, subjects completed a simple response time test. This test was conducted to check for fatigue. After all test trials with all three systems were completed and the three systems were represented to subjects, drivers responded to two questions in Chinese (one open ended, one Likert Scale [40]) to determine their preference for systems. Depending on the subject, this experiment took 70 to 90 minutes to complete.

**Question 1.** Which brake system do you think can capture your attention most effectively when the lead vehicle suddenly brakes to stop?

**Question 2.** Please give each brake system a score from 1 to 5 on its capability to capture your attention (1: fair, 5: very good, use only integers).

In the simple response time test, the identical lead vehicle was parked in front of subject vehicle, and vehicle was into neutral gear. Subjects placed their right foot on the acceleration pedal and moved as quickly as possible to the brake pedal when they saw the lead vehicle's brake light illuminated. Simple response time was the time interval from the onset the lead vehicle's brake light was illuminated until the first foot contact with the brake pedal.

**3.2. Results.** Subjects' simple response times were 0.71 s (SD = 0.07), 0.73 s (SD = 0.07), and 0.70 s (SD = 0.07) on average before, during, and after the experiment. No statistical significance was found ( $F(2, 55) = 1.28, p = 0.29$ ). Thus, on

TABLE 3: Multiple comparisons between each two brake systems using LSD test results ( $\alpha = 0.05$ ).

System	Time gap (s)					
	1.0	1.5	2.0	2.5	3.0	3.5
1 and 2	0.027*	0.233	0.021*	0.404	0.275	0.011*
1 and 3	0.746	0.749	<0.001*	0.008*	0.033*	<0.001*
2 and 3	0.056	0.378	0.082	0.070	0.322	0.118

1: conventional; 2: flashing brake; 3: flashing hazard.

TABLE 4: Number of rear-end crashes.

System	Time gap (s)						Total
	1.0	1.5	2.0	2.5	3.0	3.5	
Conventional	4	1	5	1	0	0	11
Flashing brake	0	0	0	1	0	0	1
Flashing hazard	2	1	0	0	0	0	3

average, subjects' cognitive levels did not decline with time in this experiment.

As per SAE draft Recommended Practice J2944 [37], brake response time includes reaction time (usually called perception-reaction time) and movement time. The reaction time here is defined as the time interval from the onset of the brake lamps illuminated to the first time the driver's foot releases the gas pedal, and for the movement time, from the gap pedal release onset to the first foot contact with the brake pedal. Both times were consistent as a function of time in the simple reaction time tests. On average, subjects' reaction times and movement times were 0.47 s (SD = 0.05) and 0.24 s (SD = 0.05), respectively, across the tests.

Figure 6 illustrates subjects' brake response times to three brake systems when following the lead vehicle as a function of time gap. No statistical significance was found in shorter time gap situations (1.0 s time gap:  $F(2, 60) = 3.02$ ,  $p = 0.056$ ; 1.5 s time gap:  $F(2, 59) = 0.78$ ,  $p = 0.464$ ). When time gap was longer than or equal to 2.0 s, subjects' brake response times to flashing brake systems were always briefer than for the conventional system. The flashing hazard system performed better than either the conventional or the flashing brake system. Statistical significance was found in all the four situations except the 3.0 s time gap one ( $F(2, 57) = 2.40$ ,  $p = 0.100$ ).

LSD test was adopted to examine the statistical significance between each two of the brake systems in a post hoc test. Results are shown in Table 3. Significance between the conventional and flashing brake systems can be found in 1.0, 2.0, and 3.5 s time gap situations. For all situations when the time gap was greater than or equal to 2.0 s, subjects' brake response times for the conventional and flashing hazard systems were significantly different from each other. Comparing the two flashing systems, there was no significant difference in any situation.

In terms of effectiveness (Question 1), half of the 24 subjects chose flashing brake system and the other half chose flashing hazard system. Results to Question 2 were shown in Figure 7. More than 70% of the subjects graded the flashing brake system a score equal to or higher than 4. For flashing

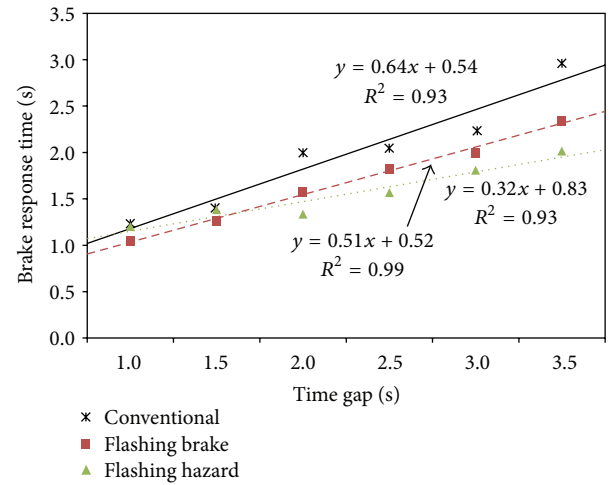


FIGURE 6: Subjects' brake response times to brake signal systems as a function of time gap.

hazard system, the number is slightly lower, about 60%. Both flashing systems were considered effective in emergency situations. Comparing the subjective evaluations of these two flashing systems, the flashing brake system was evaluated more favorably. As shown in Table 4, 15 crashes occurred in this experiment, 11 (73%) for the conventional system, 1 (7%) for flashing brake system, and 3 (20%) for flashing hazard system. One subject crashed into the lead vehicle in 4 of the 18 emergency situations, and another one for 3 times, including all four crashes when flashing systems were used. Both of them were in their 40 s (45 and 49), and their driving experience was 6 and 13 years, respectively.

**3.3. Discussion.** As shown in Figure 6, both flashing systems reduced drivers' brake response times and crash frequency overall. However, drivers' response times to the flashing hazard system were almost the same with the conventional system for very short time gaps (1.0 and 1.5 s), not as good as the flashing brake system. The clear vision field extends only about 2 to 3 degrees from the center of the visual field, and acuity declines by more than 50% when a target is only five degrees away beyond the center of the visual field [41]. In this experiment, drivers paid attention to the distance indicating arrow shown in Figure 4. When the time gap was 1.0 s, the visual angle from the arrow center shown in Figure 4 to the flashing CHMSL was about 1~3 degrees and about 8~10 degrees to the hazard lamps. For the 1.5 s time gap, the visual

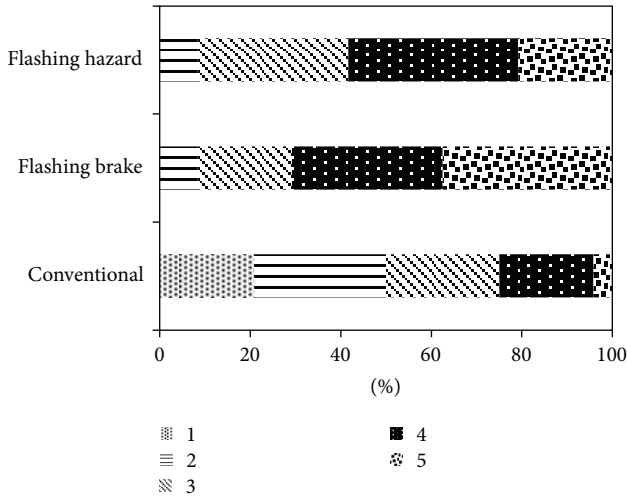


FIGURE 7: Subjective evaluation on brake systems (1: fair, 5: very good).

angles for the CHMSL and hazard lamps were about 1~2 degrees and 6~7 degrees, respectively. When the time gap was greater or equal to 2.0 s, the visual angles for all the lamps in the two flashing systems were always smaller than 5 degrees. The large visual angle of the hazard lamps in the short time gap situations greatly led to the relatively poor performance compared with the flashing brake system.

When the time gap is not shorter than 2.0 s, the minimum and maximum response time reductions by flashing brake system are 0.23 s (10%) and 0.62 s (21%), respectively. For flashing hazard system, the numbers are 0.42 s (19%) and 0.95 s (32%), respectively. Similar results have been presented in several studies. Both Gail et al. [21] and Neurauter et al. [27] found that a flash frequency at 3~5 Hz could reduce brake response time by 25~30% for CHMSL. Gail et al. [21] also found that brake lights with hazard warning lights could reduce brake response time by 0.23 s (13%).

To avoid the deviations caused by the large visual angle in shorter time gap situations, only the results in larger time gap situations were used for larger time gap regression models (see Figure 8). In the larger time gap model ( $y = kx + b$ ), the parameter  $b$ , the shortest brake response time to a brake system (time gap = 0), is about 0.43~0.63 s. In a simple reaction time test conducted by the American Automobile Association in a driving simulator [42], the 15~19 age group had a mean brake response time of 0.44 s, and the time increased steadily to 0.52 s for the 65~69-year-old group. As the positive effectiveness of flash has been proven by many studies mentioned above, it is reasonable that the  $b$  value for the conventional system is greater than that for the flashing systems. When the lead vehicle is relatively far ahead, it is assumed that the flashing lamps can be perceived as point sources, so the drivers are not sensitive to the illuminated sizes. In this case, drivers' brake response times will increase linearly as a function of time gap. The parameter  $k$  determines the increasing rate of the response time. The smaller the number is, the faster a driver responds to a brake system.

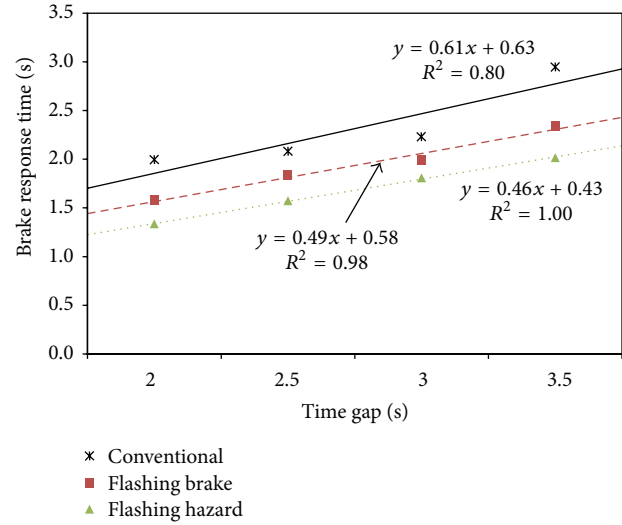


FIGURE 8: Subjects' brake response times to brake signal systems as a function of time gap.

We assume that the larger time gap models shown in Figure 8 can extend their functions to the 1.0 s time gap and 1.5 s time gap situations. As shown in Table 5, the results were compared with the experiment data and the response times calculated by the original models shown in Figure 6. For the fixed models (using larger time gap models to predict response times in shorter time gap situations), drivers' brake response times to the flashing hazard system could be reduced by 0.31 s (26%) and 0.25 s (18%) in the 1.0 s time gap and 1.5 s time gap situations, respectively. Future studies are needed to verify the effectiveness of the flashing hazard system in shorter time gap situations.

Both flashing systems have the potential to reduce drivers' brake response time compared with a conventional system. However, the frequency of the *very good* feedback for the flashing hazard system was lower than that for the flashing brake system. As per ECE R48 [35], all the stop lamps in vehicles must be red. In the US turn signal lamps can be either red or amber [17], though amber is the superior color according to a study conducted by Mortimer and Sturgis [43]. In Europe, however, only amber color is allowed. Common driving experience is that a steady red light means stop (for a traffic signal) or a vehicle ahead is braking. Turn signals flash at 1~2 Hz, slower than the flashing amber frequency used here (3.6 Hz). That similarity coupled with the limited exposure to flashing rear lamps may explain some of the outcomes in this experiment, in particular, confusion if the subject was braking, turning, or doing something else. In fact, three subjects complained about the flashing amber after this experiment. Lack of understanding and experience partly contributes to the relatively lower acceptance of flashing hazard system.

Although there is no significant difference in brake response times between the flashing brake and hazard systems, the mean values shown in Figure 6 prove that the flashing hazard system is better when the time gap is longer.



TABLE 5: Comparison of shorter gap response times (s) calculated by the original and fixed models.

System	1.0 s time gap			1.5 s time gap		
	Experiment data	Original model	Fixed model	Experiment data	Original model	Fixed model
Conventional	1.23	1.18	1.24	1.40	1.50	1.55
Flashing brake	1.04	1.03	1.07	1.26	1.29	1.32
Flashing hazard	1.20	1.15	0.89	1.37	1.31	1.12

As shown in Figure 1, the main differences between these two systems are the flashing color and illuminated size. To determine how do these two factors affect driver performance, an in-depth analysis was conducted in Experiment 3.

#### 4. Experiment 3: What Is the Effect of Flashing Lamps Color and Illuminated Size?

##### 4.1. Method

**4.1.1. Participants.** Twenty-five male subjects were recruited from by flyers and advertisements on website. Their ages ranged from 21 to 58 years ( $M = 35$ ,  $SD = 11$ ). Their driving experience varied from 1 to 29 years ( $M = 8$ ,  $SD = 8$ ). None of the participants had previously participated in either Experiment 1 or Experiment 2. One of the subjects drove with two feet, using his left foot for brake pedal and right foot for gap pedal, which is extremely rare and requires a different analysis method than for other subjects. Accordingly, his data was discarded.

**4.1.2. Procedure.** Flashing color (red and amber, 3.6 Hz) and illuminated size (large: stop lamps size + hazard lamp size; small: only stop lamps size) were both in two levels. As the positions of all the lamps did not change, the visual angles were the same with those in Experiment 2. Four trials ( $2 \times 2$ ) were tested in total. A single scenario (velocity: 80 km/h, deceleration of lead vehicle: 0.6 g, time gap: 2.0 s) was created. Subjects were required to react as soon as possible when they saw any indication of braking.

At the end, three questions were asked in Chinese.

**Question 1.** Have you noticed any color difference in the brake systems?

**Question 2.** Which flashing color do you think is more conspicuous to capture your attention, red, amber, or almost the same?

**Question 3.** Have you noticed any illuminated size difference of the brake systems?

**4.2. Results.** Subjects' mean brake response time to amber color was 0.98 s ( $SD = 0.27$ ) on average, compared to 1.09 s ( $SD = 0.20$ ) to red color, reflecting 0.11 s (10%) significantly better performance ( $F(1, 93) = 5.17$ ,  $p = 0.025$ ). See Figure 9. The mean brake response times to large and small illuminated sizes were 1.02 s ( $SD = 0.25$ ) and 1.06 s ( $SD = 0.24$ ), respectively, hardly different and not significantly ( $F(1, 93) =$

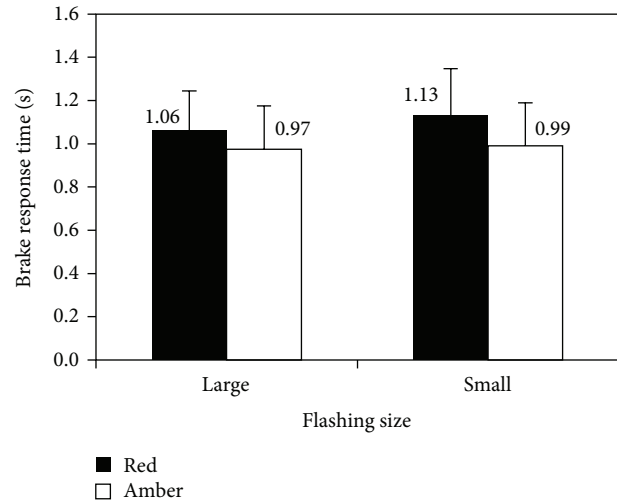


FIGURE 9: Color effect on subjects' brake response times.

0.62,  $p = 0.432$ ). The color  $\times$  size interaction was also not significant ( $F(1, 91) = 0.28$ ,  $p = 0.597$ ).

All the subjects noticed the color difference of brake systems. When asked which color was preferred, 50% (12 subjects) chose amber, 42% (10 subjects) chose red, and 8% (2 subjects) said there was no difference. Although 54% of subjects (13) reported that they had noticed the illuminated size differences among the tested brake systems, none of them could figure out the exact difference.

**4.3. Discussion.** Colors can reduce drivers' brake response times if used properly. In this experiment, subjects' brake response time to amber color was reduced by 0.11 s (10%) compared with red color. Luoma et al. [44] found that drivers' brake response times were significantly reduced by 0.11 s (15%) when the brake signals were presented in the context of amber turn signals than when they were presented in the context of red turn signals. What is very interesting is that, in this experiment, the response times to flashing amber color were also significantly reduced by 0.11 s on average compared with those to flashing red color. In a study conducted by Post [45], response times were reduced significantly by a "hazard mode" system with amber turn signal compared with red ones. Mortimer and Sturgis [43] investigated the preference color for turn signals in experiments and found that the American subjects preferred amber even when, presumably, it was not very popular in US at that time. Besides, Allen [46]

showed that amber rear turn signals led to a 5.3% reduction in involvement in two-vehicle crashes.

Besides color, illuminated size and the number of target elements can also produce cuing effects to capture drivers' attention. Increasing the number of stimuli can decrease drivers' brake response times effectively [47]. Compared with flashing brake system, there are more lamps flashing or statically on for flashing hazard system, which may partly contribute to the better performance of flashing hazard system. Although the size of a target element can also affect the attention speed [48], it did not significantly affect drivers' brake response times in this experiment, probably because the illuminated size difference of these two flashing systems is not remarkable. This is supported by feedback from subjects that none of them could figure out the exact illuminated size difference when asked after the experiment.

## 5. Conclusions

(1) Which is the most influential factor (time gap, velocity, deceleration, or brake system type) on drivers' brake response times?

Time gap showed the most significantly effect on subjects' brake response times compared with the other three factors (velocity, deceleration, and brake system type). Also, subjects' brake response times significantly increased with speed and decreased with deceleration of the lead vehicle.

(2) How do both flashing systems and the conventional system affect drivers' brake response times as a function of time gap?

Three linear regression models were built to predict the brake response time to each emergency stop signal system. Brake response time increased with time gap for all three systems. Overall, the conclusion that both flashing systems can reduce brake response times effectively is strengthened by the subjective evaluations and the decrease in the number of crashes when flashing systems were used. Subjects' responses to the flashing hazard system were not as positive as the flashing brake system in the scenarios examined in this study, when the time gap was shorter (1.0, 1.5 s). Compared with flashing brake system, however, flashing hazard system was more effective in reducing brake response times for longer time gaps (greater than or equal to 2.0 s) situations. However, in the real world, the shorter time gaps are the major safety concern. The effectiveness of the flashing hazard system in shorter time gap situations needs to be reexamined in the future studies, because the visual angles of the flashing hazard lamps in this study were relatively greater than those in the real world traffic.

(3) How do colors (red and amber) and illuminated sizes (large and small) affect drivers' brake response times?

Amber color improved subjects' brake response times by 0.11s significantly compared with red color, but the illuminated size did not affect as much comparatively in this study. Half of the subjects preferred amber as a more attractive color. The promising results shown in this study probably can be improved by education.

As per SAE draft Recommended Practice J2944 [37], brake response time could be divided into two parts (reaction time and movement time). For future studies, they should be analyzed separately.

The luminance of the brake systems projected on the screen was not measured when the experiments were conducted. Because of the aging of the projectors in the simulator, the luminance values could not be remeasured correctly. The lack of the values may make the results of this study difficult to compare with other research.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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