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The influence of in-vehicle speech warning timing on drivers' collision avoidance performance at signalized intersections

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ABSTRACT

Collision warning systems have been identified as an effective technique for avoiding accidents. In such a system, the delivery time of warning messages is a crucial factor that influences the success of collision avoidance. This study therefore contributes by providing experimental analyses on a range of delivery times of warning messages, which has been overlooked in past studies. Using simulator-based techniques, experimental scenarios are specifically designed for accounting the red-light-running events at intersections and drivers are recruited to test on different settings of warning timings. Several measures including brake reaction time, alarm-to-brake-onset time and deceleration are adopted as reflections of drivers' performances under the collision avoidance process and they are connected to several factors by mixed effect models. According to the results, the collision warning system actually can largely reduce the occurrence of red-light-running collisions, more importantly it reveals the influence of warning timings within the predefined ranges and 4.0 s or 4.5 s may be a proper warning timing for the right-angle collisions accused by red-light-running vehicles in this study. Besides, effects from directional information embedded in warning messages are also investigated in this study. Findings are important to the design of collision warning systems especially in the aspect of warning timings.

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1. Introduction

Among all traffic crashes, a large portion of them were occurred at intersections (PIARC, 2008). For instance, the crashes occurred at junctions in Norway account for about 40% (Elvik and Vaa, 2011) of all crashes. In the United States, the intersection or intersection-related crashes account for approximately 27% of all crashes (FHWA, 2011). In fact, intersection areas contain many conflict spots, and intersection-related areas usually have many traffic markings and signs that demand additional mental workload of drivers. These aspects may highly enhance the chance of collisions especially when conflicting vehicles appear. Accident data showed that the most important reason of traffic accidents at intersections was red light violation behavior. For example, in the US, red light running (RLR) contributed to around 260,000 crashes each year of which about 750 were fatal (Retting et al., 1999). Red light running crashes were also found to be more severe than other types of crashes (Yousif et al., 2014). Towards this, the collision warning system (CWS) is developed as an important tactic approach for avoiding crashes. RLR-CWS detects all vehicles approaching an intersection and identifies RLR vehicles based

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on vehicles' real-time positions and speeds with sensors equipped in vehicles and devices at intersections, such as detecting radar. If a RLR vehicle is approaching the intersection, RLR-CWS can timely provide warning information to drivers in order to avoid the potential collision with the RLR vehicle (Atev et al., 2004; King and Refai, 2011). Usually, it posts lights or sound signals to drivers if potential crashes are detected. Such a system will affect driving performances and collision-avoidance abilities of drivers and further affect the success rates of collision avoidance.

RLR-CWS is one of technology-based solutions to enhance drivers' crash response capability in hazardous situations. The collision warning technologies have been widely explored for their application scenarios, such as detecting pedestrian conflicting with vehicles by stereo vision (Llorca et al., 2012), evaluating different types of Cooperative/Chain Collision Avoidance applications in a freeway and an urban road scenarios (García-Costa et al., 2013) and releasing warning to unprotected right-turning vehicles at two-way stop-controlled rural intersections (Dabbour and Easa, 2014). Past studies have illustrated many advantages of CWS in mitigating crashes. For example, Jamson et al. (2008) indicated that all drivers could benefit from the forward collision warning system. Ben-Yaacov et al. (2002) found that collision warning systems could help drivers estimate headway more accurately and consequently to maintain longer and safer headways. Lee et al. (2002) showed that, compared with the no-warning condition, an early rear-end collision avoidance warning system reduced the number of collisions by 80.7% and the collision severity by 96.5%.

In such warning systems, auditory messages are usually used to remind drivers of possible hazardous situations. Liu and Jhuang (2012) showed that auditory message with spatial compatibility could significantly improve drivers' performance in reacting to the divided attention task and making accurate stimulus-response task decisions. Compared to the simple beep sound, speech messages were suggested because they could lead to a significant reduction of perception-reaction time of drivers (Chang et al., 2008).

After receiving a warning message, drivers need certain amount of time for reacting and then performing appropriate actions to avoid the crash. Therefore, the delivery time of warning messages could seriously influence the effectiveness of the warning system (Janssen and Nilsson, 1993; Ho and Spence, 2009; Tang and Yip, 2010). Werneke and Vollrath (2013) found that the early warning signal showed a positive effect in avoiding accidents at intersections. In fact, drivers could avoid most collisions if the warning messages were delivered in advance of the potential accidents with sufficient amount of time. Lee et al. (2002) found that later warning timing was also able to reduce collisions, but it was less effective than the earlier warning timing.

Abe and Richardson (2006) indicated that drivers' trust would be reduced if they had already made a decision to brake prior to an alarm. Under such a condition, drivers were more likely to ignore the system and relied on their individual judgments of impending collisions (National Highway Traffic Safety Administration, 2005). Abe and Richardson (2004) tested three different conditions of warning timing: early timing, middle timing and late timing under a forward collision warning system. The results indicated that early alarm timing would lead to well-prepared responses to an imminent collision than middle and late timing. However, earlier warning timing was more likely to be functioned as a false alarm which in turn led to a reduction in future use of the collision warning system (Seller et al., 1998).

Therefore, the delivery time of warning messages is a crucial factor to the design of CWS. With an appropriate setting of warning timings, CWS should be able to provide drivers with in-time, precise and reliable forecasts of impending accidents. In fact, there are limited studies considered this aspect in past, and existing literatures have only examined qualitative influence of warning timings. For example, the influence of in-advance deliver times of warning message was investigated using two comparative categories: early timing and late timing (Werneke and Vollrath, 2013; Abe and Richardson, 2005, 2006), or three categories: early timing, middle timing and late timing (Abe and Richardson, 2004). There still lacks analyses on a range of warning timings, which actually can illustrate more detailed relationships between different warning timings and drivers' performances on collision avoidances. With more defined categorization of warning timings, it is also useful to find a more appropriate range of warning times for further design of collision warning systems.

In addition, directional information is a part of the warning messages, which can inform drivers with the orientation of potential collisions. In detail, the directional information indicates whether the direction of collision is on the drivers' left side or right side. Such information is supposed to reduce drivers' mental workload by narrowing their vision of attentions and therefore might help drivers take timely crash avoidance actions. However, Yan et al. (2014) concluded that a directional warning may delay the mental processing of the warning information and cause insufficient decelerations under a late warning timing (3 s). Thus, the directional information combined with different warning timings could result in various crash avoidance behaviors and performances, which will be inspected in this study.

Towards this end, this study is going to investigate the impacts of warning timings and directional information on collision avoidance performance based on driving simulator experiments, which have demonstrated great potentials for examining the influence of CWS on driving performance (Suetomi et al., 1995; Lee et al., 2002; Yamada, 2002; Becic et al., 2013; Fort et al., 2013; Wu et al., 2014). More specifically, instead of use arbitrarily designed earlier and later warning timings, this study initially discusses a practical range of in-advance delivery time of warning messages (varied from 2.5 s to 5.5 s) for avoiding collisions from RLR vehicles and examines drivers' reactions and the effectiveness of collision avoidance under a set of continuously scatter points within the predefined range of warning timings. In addition, the different in-advance delivery times are also combined with a binary choice of directional information of the warning messages.

2. Experiments

2.1. Participants and apparatus

There are total 45 participants recruited in the current study, of which 23 participants are male, and 22 are female. The experiment requires that participants have obtained a driving license for at least three years and driven at least twenty thousand kilometers per year. The average age of participants is 35 years old ranging from 31 to 39. The impact of age on driving behaviors and crash avoidance performances is complicated, which might be largely entangled with the factors of warning conditions. For example, age can influence physiology signals during driving on the same road (Zheng, 2003). Therefore this experiment intentionally recruited drivers under such a narrow age band and they are believed to exhibit relatively mature and stable driving performances in responding to emergencies. Such a design can reduce the variation due to age and hence illustrate more clear impacts of warning conditions.

The driving simulator used for this study is able to simulate various road traffic environments and driving scenes, as shown in Fig. 1a. The vehicle cockpit in the simulator is designed in full accordance with the human body and the inside components, including the brake pedal, throttle, steering wheel and gear are completely identical to a real vehicle (a Ford Focus). The driving simulator can also provide mimetic environmental noise and the equipped vibration simulation system and one degree of freedom motion platform can imitate the feeling of motion in order to largely replicate the realistic situations. This driving simulator has a 300-degree front view of display system with simulated back mirrors. Fig. 1b is a screenshot from a test scenario in the experiment.

2.2. Delivery time of warning treatments

In this experiment, fourteen scenarios are designed with different warning messages that characterized by two factors: the in-advance delivery time (seven kinds) and the level of directional information (two levels), and the no warning condition is regarded as baseline, as shown in Table 1.

Considering that warning messages are delivered too late, the drivers whose vehicles with CWS will not have enough time to stop their vehicles before entering the intersection to lead to collisions with RLR vehicles. The delivery time of warning message needs to satisfy drivers to identify potential risk and takes the corresponding collision avoidance maneuvers. Thus, 2.5 s is defined as the latest delivery time of warning that should at least allow drivers to react to the warning and then engage brake action before the collision, which is able to cover most situations and it has been widely accepted in many studies (Lerner, 1993). However, if warning message is delivered too early, it is actually difficult to judge the intention of conflicting drivers, and only a small range of vehicles which have high speed can be detected as RLR vehicles at high prediction accuracy, which could increase user's unbelief of the CWS. In this study, 5.5 s is defined as the earliest delivery time of warning. So, the range of in-advance delivery time of warning message given in this experiment is 2.5–5.5 s, and the warning timing is set with 0.5 s interval, including seven kinds of warning timing in all. In addition, the two levels of directional information are: non-directional information warning message using voice “please watch the vehicle running the red light” and directional information warning message using voice “please watch the vehicle running the red light on you right”.

2.3. Scenario designs

This study focuses on right-angle collisions caused by red-light running. Specifically, the conflicting vehicle attempts to run a red light at a signalized intersection while the test vehicle (driving simulator) is on green phase. Fig. 2a illustrates the diagram of such a designed scenario. In order to test drivers' performance under the hazardous conflict, the intention of the

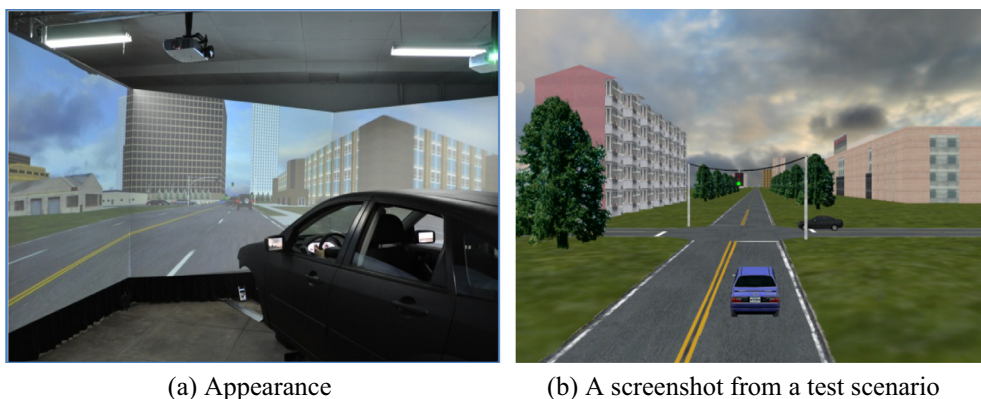


Fig. 1. A illustration of the driving simulator.

Table 1
Descriptions of warning conditions in this experiment.

Treatment ID	Warning	Directional information	Warning timing (s)
1		Directional	2.5
2			3
3			3.5
4			4
5			4.5
6			5
7	Yes	Non-directional	5.5
8			2.5
9			3
10			3.5
11			4
12			4.5
13			5
14			5.5
15			No

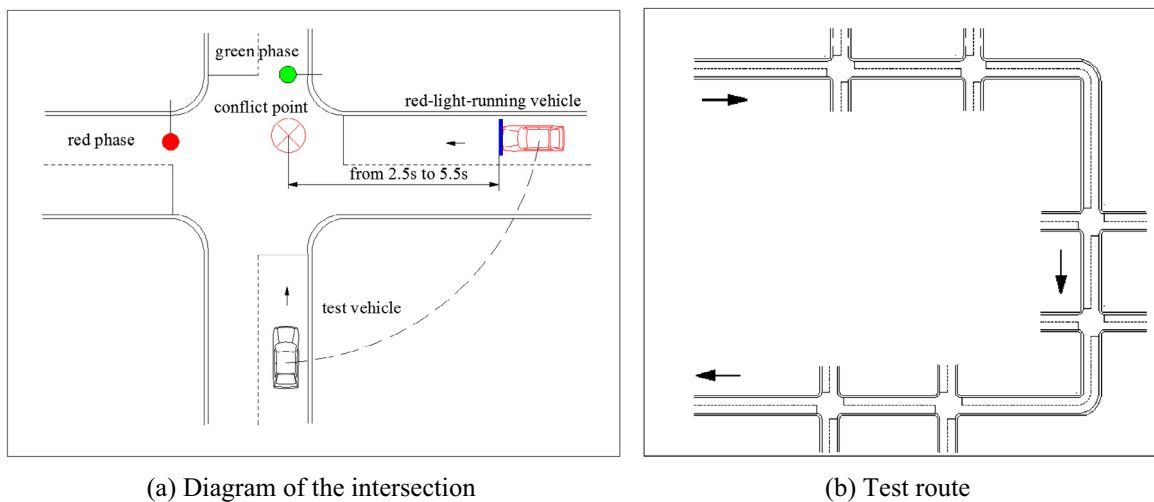


Fig. 2. Collision avoidance warning scenario at the experimental intersections.

scenario design is to provide a high chance of collisions between the test vehicle (driving simulator) which is operated by the recruited participants and the RLR vehicles which are triggered by the driving simulator.

In this study, the TTC (time to collision) sensors are used to monitor the approaching time of simulator to the conflict point at the intersection. When its approaching time is 7 s to the conflict point, the TTC sensor would trigger the RLR vehicle start to cross the intersection with a velocity of 72 km/h. Because the approaching time of the RLR vehicle to the conflict point is also designed as 7 s, which indicates that the RLR vehicles are initiated at the 140 m downstream of the conflict point, the collision of these two vehicles will occur exactly at the conflict point as long as the velocity of driving simulator does not change. That is, the RLR vehicles are in motion if the estimated travel time of the test vehicle (driving simulator) to the conflict point is 7 s. Then, once the approaching time of simulator to the conflict point satisfies a predefined warning time value (varied from 2.5 s to 5.5 s), the audio information will be released to alert the driver to the conflicting RLR vehicles.

Each experimental scene is built up based on a test route connected by six intersections, as shown in Fig. 2b. According to the design of the experiment, three of the six intersections are randomly selected with triggered conflicting vehicles in each test run, whereas the rest 3 intersections are clear without any distractions to participant drivers. Under such design, each driver is required to perform 5 independent test runs in order to provide responses to the total 15 different warning treatments. To be noted, the arrangement of test orders of the 15 warning treatments is also random to each driver. During the simulated driving, the signal phase along the route for the test vehicle is always in green, and it is always red in the direction of RLR vehicles. The simulated roadway is a two-way two-lane road and the posted speed limit is 80 km/h. As aforementioned, these scenarios are carefully designed so that test vehicles will collide with the red-light-running vehicle unless the test vehicle accelerates or decelerates when it approaches intersections. The audio warning is delivered in the test vehi-

cle if the travel time between the RLR vehicle and the conflict point reaches to the designed warning timing (varied from 2.5 s to 5.5 s).

2.4. Variables

Each driver is required to test under the total 15 different warning treatments and hence there are 675 intersection-scenarios of tests. Several critical variables reflecting driving performances and the results of collision avoidance are then extracted from these scenarios. In referring to the definition of driving performances from Evans (1991) and Roskam et al. (2002), this study uses brake reaction time, alarm-to-brake-onset time, and deceleration to reflect the driving performances. Fig. 3 shows the velocity change curve when the drivers approaching the signalized intersection to help define these variables and these variables are explained as follows.

Brake reaction time: the time is measured from the time at which the test vehicle arrives at the specified position before entering the intersection, with the RLR vehicle being triggered at the same time, to the time at which the driver of the test vehicle depresses the brake pedal.

Alarm-to-brake-onset time: the time is measured from the time at which the warning information releases, to the time at which the driver of the test vehicle starts to brake.

Deceleration: the change rate of velocity during the period from the time of brake to the time of the largest braking.

Each subject has repeated measures in respect to the 15 different warning treatments. Mixed effect models therefore are built to connect these variables with factors. Warning timing and directional information are treated as within-subjects factors, and gender is treated as between-subjects factor. A value of $P < 0.05$ is adopted as the level for significance. In addition, logistic regression is used to evaluate statistically significant differences for different warning conditions correlated to chances for the occurrence of crashes.

3. Results and analyses

3.1. Responses after warning

The intention of collision warning systems is to provide drivers information about anticipated crashes. However, experienced drivers might be able to perceive the threat of impending collisions in earlier time and then take actions to avoid accidents in ahead of the delivery of warning messages, especially in the situations of late delivery time of warning messages.

Fig. 4 illustrates the proportion of scenarios in which drivers respond after the delivery of warning messages. According to the results, drivers were more likely to brake after the delivery of warning messages for earlier delivery time and therefore

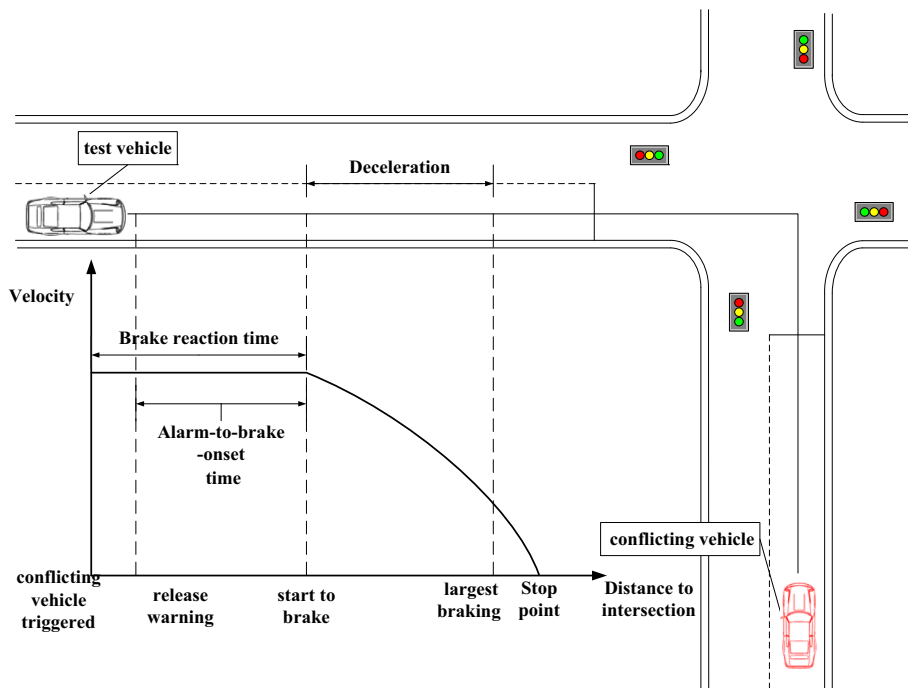


Fig. 3. Relationships between velocity curves and variables of driving performances.

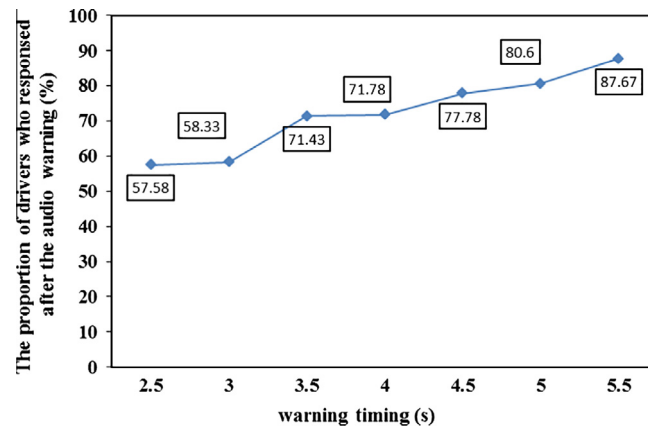


Fig. 4. Proportions of drivers who response after the audio warning.

Table 2

Mean driving performance within different categories of factors.

Conditions		Brake reaction time (s)	Alarm-to-brake-onset time (s)	Deceleration (m/s/s)	Chances for the occurrence of crashes (%)
Gender	Male	3.29 ± 1.46	0.99 ± 0.41	3.29 ± 1.94	4.48
	Female	3.29 ± 1.62	0.98 ± 0.39	3.48 ± 1.94	8.18
Directional information	Non-directional	3.37 ± 1.54	1.05 ± 0.42	3.59 ± 1.82	5.43
	Directional	3.11 ± 1.42	0.92 ± 0.38	3.33 ± 1.74	2.54
Warning timing (s)	None	4.19 ± 2.10	NA	2.16 ± 2.09	40
	2.5	4.19 ± 1.72	0.94 ± 0.40	3.41 ± 2.10	13.04
	3.0	3.68 ± 1.53	1.06 ± 0.44	3.61 ± 1.92	1.09
	3.5	4.16 ± 1.43	1.14 ± 0.45	4.01 ± 1.99	9.89
	4.0	3.23 ± 1.18	0.91 ± 0.38	3.69 ± 1.75	0
	4.5	2.85 ± 1.17	0.87 ± 0.30	3.27 ± 1.53	1.09
	5.0	2.34 ± 0.97	1.12 ± 0.44	3.24 ± 1.59	2.2
	5.5	2.16 ± 0.72	0.90 ± 0.35	3.00 ± 1.35	0

the contribution of late warning for collision avoidance might be limited. Specifically, only 57.58% of scenarios benefited from the warning if the message was delivered only 2.5 s ahead of the predicted occurrence of accidents. Such late warning message might disturb the normal operation of drivers and their own judgments on potential collisions. In contrary, the early warning could provide drivers more time to process the information and then make well-prepared actions in response.

3.2. Brake reaction time

Table 2 lists driving performance with different factors, including gender, directional information and warning timing.

According to the mixed effect model, warning timing ($F = 49.821$, $P < 0.001$) and directional information ($F = 7.498$, $P = 0.007$) illustrated significant impacts on brake reaction time. However, there was no significant difference ($F = 0.619$, $P = 0.436$) between male and female drives in terms of the brake reaction time. Fig. 5 presents the mean brake reaction time for different levels of warning conditions as well as the hypothesis test results in terms of the mean differences between the control group and groups under other warning conditions. In this figure, the “N” is represented for non-directional warning and “D” is represented for directional warning. In average, drivers’ brake reaction time for the control group is the largest in comparing to other conditions, which could reveal that the drivers under no-warning condition response to emergent events more slowly with widest fluctuations (referring to Table 2). Compared with the reference group (no-warning), using warning messages result in less brake reaction time of drivers, especially in the condition of earlier warning timings (4.5–5.0 s). It also useful to note that, the brake reaction time for late warning timings (2.5 s and 3.0 s) do not have significant differences in comparing to the group of no-warning, indicating that late warning timings might disturb drivers’ awareness of impending accidents and hence postponed the timings for braking.

3.3. Alarm-to-brake-onset time

Sample scenarios of which drivers taken brake actions prior to the delivery of warning message were removed from the entire dataset, since in these scenarios warning messages were delivered later than the drivers’ reactions to the impending collisions. A mixed effect model was built in similar way to connect the alarm-to-brake-onset time to gender, warning timing

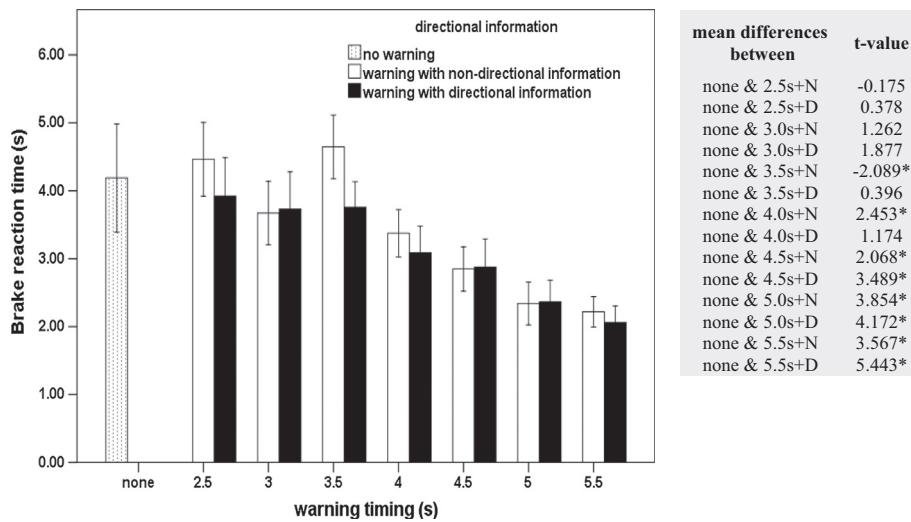


Fig. 5. Mean brake reaction times under different warning conditions.

and directional information. The result showed that different warning timing ($F = 3.559, P = 0.004$) and directional information ($F = 4.449, P = 0.036$) exhibited significant influences on alarm-to-brake-onset time. However the effect of gender ($F = 0.022, P = 0.884$) was not significant. Fig. 6 illustrates mean alarm-to-brake-onset time for situations of different combinations of directional information and warning timings. In this experiment, there were no clear patterns of impact of warning timings on alarm-to-brake-onset time.

3.4. Deceleration

The influences of gender, warning timing and directional information on deceleration were examined through a similar mixed effect model. The effect of warning timing was significant ($F = 0.6813, P < 0.001$). However directional information ($F = 2.466, P = 0.117$) and gender ($F = 0.249, P = 0.620$) did not have significant impacts on deceleration rate of drivers. Fig. 7 presents the mean deceleration for different levels of warning conditions as well as the hypothesis test results in terms of the mean difference between the control group and other groups under other warning conditions. There are significant differences of deceleration between the control group and other groups of different warning timings. According to Table 2, the mean deceleration value for the cases with warnings is higher than that with no warning and the case of no warning has a larger deviation. It was obvious that scenarios with warning messages had higher decelerations than the situations without warning messages. Most of drivers would reduce the speed to avoid collision and they became rely on the warning messages, which demonstrated that warning could reduce the possibility of collision event. On the contrary, drivers without collision warning system, who needed to judge whether there was danger on their own experience. Moreover, compared with no

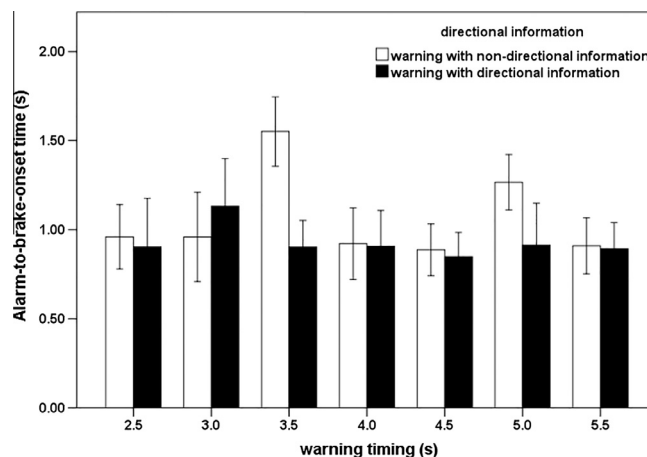


Fig. 6. Alarm-to-brake-onset times under different warning conditions.

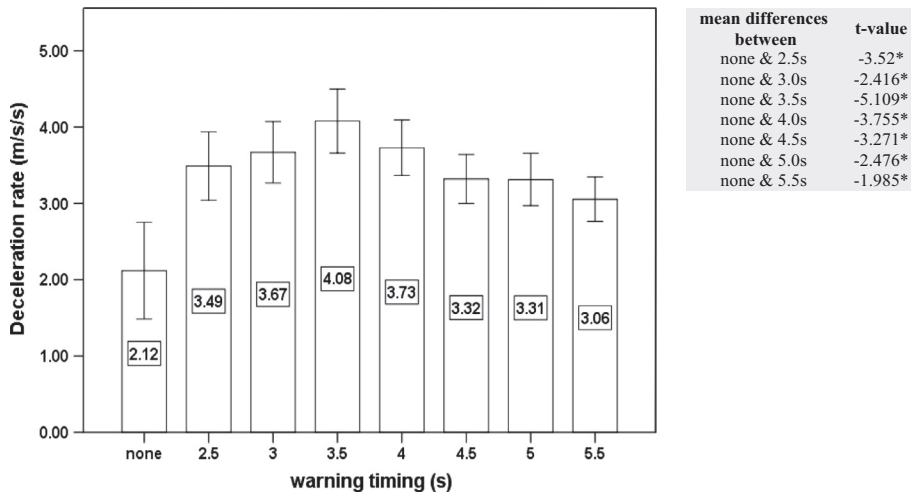


Fig. 7. Mean decelerations under different warning conditions.

warning, the delivery time of warning varied from 2.5 s to 3.5 s could slow down the fluctuations of the deceleration; the delivery time of warning varied from 4.0 s to 5.0 s, with the delivery time of warning earlier, the deceleration gradually reduced as well as the standard deviation. That was, with the collision warning system released earlier, drivers heard the warning, and they may move to the pedal and pressed slowly and continuously until out of danger. However, the earliest delivery time of warning (5.5 s) did not make more contribution in reducing brake reaction time compared with no warning. The result suggested that earlier warning could contribute to slow the intensity of deceleration measure, thus reduced the possibility of rear-end crash caused by imminent brake.

3.5. Chances for the occurrence of crashes

As discussed, warning messages affected drivers' performances when they were approaching signalized intersections with potential conflicts due to red-light-running actions of vehicles from another direction. Such influences could specifically be exerted to drivers' performances through measures including brake reaction time, alarm-to-brake-onset time and deceleration rate. In fact, the intention of warning messages is to assist drivers in avoiding impending collisions. Therefore, it is important to evaluate the effectiveness of such a system. Without controlling other variables, the marginal effect of different warning time is illustrated in Fig. 8 through the observed crash rates in the experiment.

In this study, the crash rate was 40% which was highly greater than any scenarios with warning messages and it was clear that the collision warning system was effective to enhance the drivers' abilities for avoiding crashes at intersections since for

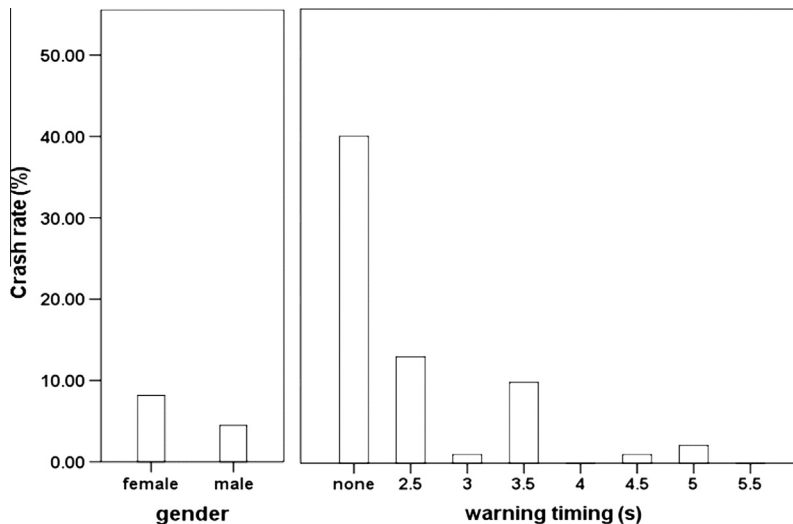


Fig. 8. Crash rates within different categories of gender and warning conditions.

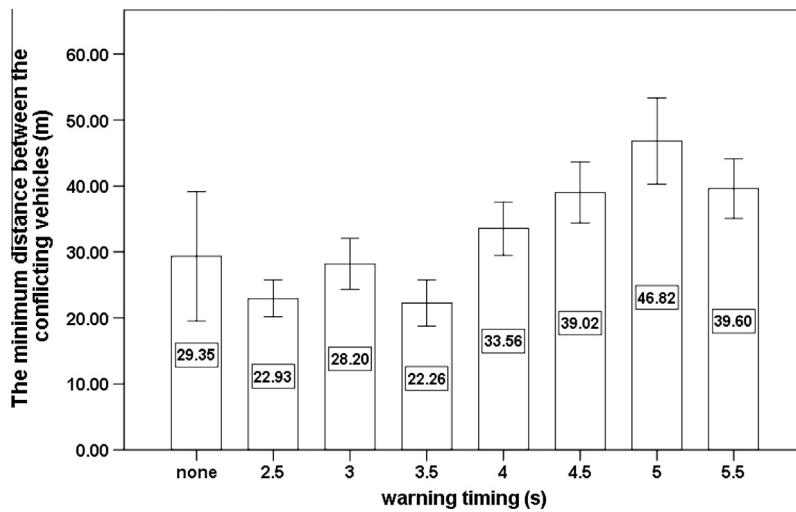


Fig. 9. The minimum distance between the conflicting vehicles under different warning conditions.

Table 3

Results of the logistic regression model.

Variables	B	S.E.	Wals	df	Sig.	Exp (B)
Gender (female)	0.757	0.358	4.463	1	0.035*	2.131
Warning timing	−0.821	0.103	63.642	1	0.000*	0.440
Constant	−0.688	0.345	3.971	1	0.046*	0.503

* Indicates that the variable is significant at a 95% confidence level.

scenarios without warning messages. The crash rate was also varies according to different levels of warning timings. Fig. 8 shows a trend that as the delivery time of warning message increases, the crash rate reduces. Interestingly, it was found that the crash rate for the 3 s warning timing condition was an exception lower than the adjacent warning timing conditions (2.5 s and 3.5 s), presumably owing to the random effect. Further, Fig. 9 illustrates the minimum distance between the conflicting vehicles for no-collision cases under different warning timing conditions, which implies the collision risk of conflict. It was found that the minimum distances between the conflicting vehicles for the late warning timing conditions were smaller than those for the early warning timing conditions, which indicated that early warning timing conditions could increase the minimum distances between the conflicting vehicles and reduced crash risk. In addition, Fig. 8 provides the crash rates within different categories of gender. Female drivers exhibited higher chances of crashes than male drivers in this experiment.

Logistic regression analysis is then applied to investigate the impacts of independent variables including warning timing, directional information of warning and drivers' gender on outcome of collision avoidance. The hypothesis testing of the coefficients is based on a 0.05 significance level. According to the results from logistic regression analysis, gender and warning timing have significant effects on the crash rate ($P < 0.05$), whereas directional information ($P = 0.34$), and the interaction between directional information and warning timing ($P = 0.74$) do not have significant effects on the crash rate. Table 3 shows the final model contains only the variables that presented significant effects on the crash rate and the estimation results. Referring to different delivery time of warning message, a setting of earlier warning timing had lower collision occurrence likelihood than the situation of later warning timing. For the earlier delivery time of warning message, drivers in simulator might have sufficient time to process the information. Treating warning timing as a continuous variable, increasing one second earlier warning can result in 56% of reduction in the crash involvement rate (Exp (B) = 0.440).

According to the logistic regression result in Table 3, the crash involvement rate for female drivers is 2.13 times of that for male drivers (Exp (B) = 2.131). Over the 675 experimental tests, a total of 43 crashes (6.2%) are observed. Considering for the gender, 61.9% of the 43 crashes were involved by female drivers. In the group of no warning, the crash rate for female driver is 28.9% (13 crashes) and that for male driver is 11.1% (5 crashes), which demonstrated that female drivers are more likely to involve a collision than male drivers under no-warning condition. In the group of warnings, the crash rate for female drivers is down to 2.83% and close to the rate for male drivers (2.22%). The results indicate that the female drivers could get more benefit from warning than male drivers. However, the gender difference was identified in the logistic regression model but not well embodied from the perspective of driving behaviors in Table 2 that describes average brake reaction time and deceleration rate for all 15 warning conditions. If focusing on the no-warning case, the average brake reaction time is 5.31 s for

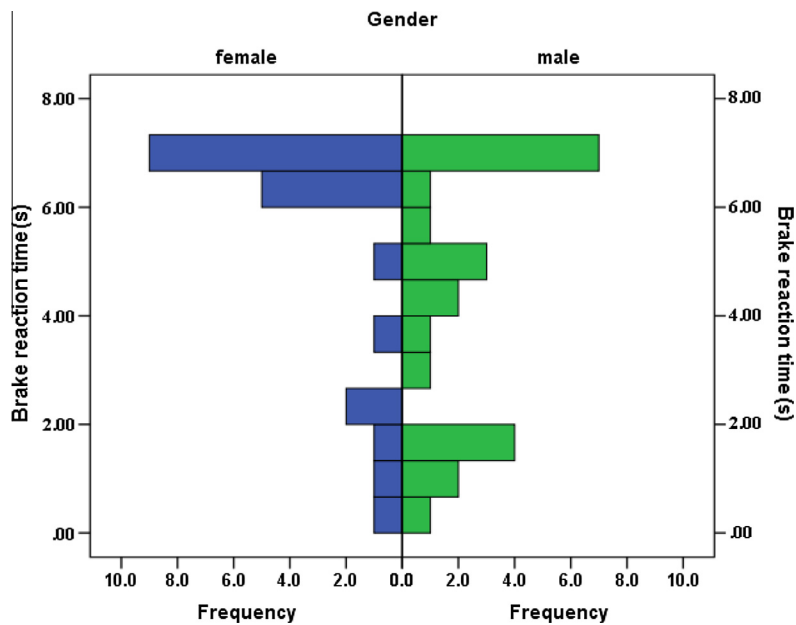


Fig. 10. Histogram comparisons of brake reaction time between female and male drivers under no-warning condition.

female drivers with a standard deviation of 2.31 s and 4.40 s for male drivers with a standard deviation of 2.36 s. Nevertheless, the gender difference cannot be analyzed by T-test because Fig. 10 clearly indicates that the brake reaction time data do not follow a normal distribution ($P < 0.001$ according to the Kolmogorov–Smirnov test). Since the mean brake reaction time for the cases of collisions under the no-warning condition is 5.64 s, it is applied as a threshold value to analyze the difference in the brake reaction time distributions between female drivers and male drivers. Consequently, among the 22 female drivers without warning, 15 of them had brake reaction times longer than 5.64 s; however, there are only eight of 23 male drivers whose brake reaction times were longer than 5.64 s. The difference in brake reaction time distributions between male and female drivers is statistically significant based on the likelihood ratio test ($P = 0.004$). Therefore, without warning female drivers tend to have longer reaction time than male drivers, which is consistent with the finding that female drivers have a higher crash involvement rate than male drivers.

4. Discussion and conclusions

The presented study was intended to investigate the function of a collision warning system on drivers' performances during the process of collision avoidance as well as the effectiveness of the system. Scenarios were specifically designed for right-angle collisions accused by red-light-running vehicles. These experiments were designed to test different warning timings and directional information. The results addressed several aspects of this objective.

Brake reaction time is an important variable indicating drivers' performances in avoiding traffic accidents, and it is believed that smaller reaction time will benefit driving safety. Evans (1991) indicated that smaller reaction time could reduce the probability and severity of crashes. This study demonstrated that vehicles with a warning system in general led to smaller reaction time if warning messages were delivered in an appropriate timing. However, later delivery time of warning message might not be able to assist drivers in avoiding collisions and even obstruct drivers' own judgments. In this study, later deliveries of warning messages (2.5 s and 3.0 s) presented similar reaction performance to the situation of no warnings. According to the experiment results, it was found that the brake reaction time under directional information warning messages was largely decreased in many scenarios. During the process of drivers' reaction, some of these drivers needed to verify the message by observing the red-light-running vehicle. If drivers had the information of the direction of the violator vehicle, they might need less time to locate the violator vehicle, and hence performed faster reactions.

The deceleration was also varying according to the different setting of warning timings. For scenarios without warning messages, a great portion of drivers did not aware the potential collisions and hence did not take brake actions, or some drivers perceived the occurrence of collisions in a very later time and they might give up any possible actions to avoid the accidents because the driving environment was not real and the remainder time before the collision was short. According to this experiment, early delivery of warnings led to smaller decelerations since drivers could evaluate the time distance from their current location to the confliction point, and the early warnings provided sufficient time for drivers to take actions. Therefore, drivers tended to take modest decelerations which were more comfortable than the severe decelerations. Following such trend, as the in-advance delivery time decreased, drivers needed to take heavier brakes in order to avoid the collisions. If the messages were delivered in very late timings, the mean value of decelerations increased. Under such situations, the

short time remained before the accident combining with release of warning caused drivers to press brake pedal more heavily.

It was useful to examine the effectiveness of the warning system using observed crashes in this experiment. Even events of crash were designed to occur in these scenarios; due to the collision warning system, the chance of collision was relatively small (the overall rate of crash was 6.5%).

Results showed that warning messages should be delivered as early as possible so that drivers could have more time to respond to critical situations, a result in line with other similar investigations (Lee et al., 2002; Abe and Richardson, 2004; Jamson et al., 2008; Chang et al., 2008). However, the earlier a warning occurred, the more likely it was to be interpreted as a false alarm because the conflicting vehicle could have enough time to decelerate if they could aware the potential collisions and consequently the predicted collision might not happen, which in turn led to a reduction in drivers' future use of the system. Therefore it was necessary to choose an appropriate warning timing in designing the system. Based on this study, 4.0 s or 4.5 s might be proper choices.

This study contributed a simulator-based experiment in examining the influence of a range of warning timings on drivers' performances during the process of collision avoidance, and on the effectiveness of a collision warning system. In addition, the impact of directional information was also investigated. Both earliest and latest delivery time of warning messages could have disadvantageous influence on usage of this system. It was important and necessary to test a range of warning timing in the experiments, which had been overlooked in past studies. With the experimental data, mixed effect models were built in order to connect factors including warning timing, directional information and gender to dependent variables. And in this study brake reaction time, alarm-to-brake-onset time and deceleration were used to reflect the drivers' performance in situations of collision avoidance. The results strongly illustrated that the collision avoidance system was effective in enhancing drivers' performances and successfully assisting drivers to avoid the potential accidents. Moreover, earlier delivery of warning messages resulted in shorter reaction times and lower deceleration rates which would be benefit to collision avoidance.

Overall, this study provided important insight into a range of delivery time of audio warning messages which were delivered to remind drivers who were approaching intersections during the green phase to be alert to conflicting illegal RLR vehicles. An important limitation of the current study is that the brake reaction time is relative, which may result in analyzing data only for trend and cannot be directly compared with other experimental results. Besides, the results cannot be verified in real situations because of high risk. For future research, it is interesting to incorporate electroencephalogram and eye-movement-tracking equipments to monitor psychological activities of drivers and then reveal explanations on drivers' behaviors under collision warning systems. If the speed variation of the conflicting vehicle is large, its travel time to the confliction point would be difficult to anticipate. Therefore, it is also useful to find strategies for identifying red-light-running vehicles more efficiently.

Conflict of interest

The authors do not have a direct financial relation with any commercial entity mentioned in their paper that might lead to a conflict of interests for any of the authors.

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