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The effects of warning characteristics on driver behavior in connected vehicles systems with missed warnings

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ABSTRACT

With emerging new technologies, the vehicles in the future with connected vehicle systems (CVS) will be equipped with the ability to communicate with each other and aim to provide drivers with information in a timely and reliable way to improve driver safety. This study was designed to investigate the interaction effects of warning lead time (2.5 s vs. 4.5 s), warning reliability (73% vs. 89%), and speech warning style (command vs. notification) on driver performance and subjective evaluation of warnings in CVS. A driving simulator study with thirty-two participants was designed to simulate a connected vehicle environment with missed warnings due to failures in the communication network of the CVS. With regard to the response types, the results showed that notification warnings led to a lower probability of braking response and a higher probability of braking and steering response compared with command warnings. The results showed command warnings led to a smaller collision rate compared to notification warnings with the warning lead time of 2.5 s, whereas no significant difference of collision rates was found between two warning styles when the warning lead time is 4.5 s. These results suggest notification warnings should be selected when the warning lead time is longer and the warning systems are highly reliable, which resulted in higher safety benefits and higher subjective rating. Command warnings could be selected when the warning lead time is shorter since they led to more safety benefits, but such selection has to be made with caution since command warnings may limit drivers' response type and were perceived as less helpful than notification warnings.

1. Introduction

With vehicular injuries and deaths in the United States spiking for the first time in nearly fifty years, newly-developed Connected Vehicle Systems (CVS) may become one of the most promising technologies to improve driver safety and impact public health issues. It has been predicted that connected vehicle technology could prevent up to 80% of vehicle crashes involving unimpaired drivers (Najm et al., 2010). With emerging wireless communication technologies, vehicles will be equipped to communicate with each other as to surrounding vehicles by exchanging vehicle status and motion data via Dedicated Short-Range Communications (DSRC) network (Kenney, 2011). The cooperative collision warnings supported by these connected vehicle systems, including Forward Collision Warnings (FCW) and Intersection Movement Assistant (IMA), inform drivers about traffic situations ahead of time, especially those that are out of their line of sight. With such warnings, drivers are warned about potential hazards at an early enough stage to properly respond and avoid accidents.

The impact of designed warning parameters on driver performance is increasingly important now that cooperative collision warnings may assist drivers. Existing empirical studies have identified warning timing and warning reliability as two critical parameters in determining the effectiveness of collision warning systems with respect to driver safety, regardless of warning modalities and formats. Studies regarding warning timing of in-vehicle collision warning systems consistently have concluded that early warnings led to more timely braking and a longer braking process, resulting in greater driver trust of the warning systems, and reduced collisions overall (Abe and Richardson, 2004, 2005, 2006a; Lee et al., 2002; McGehee et al., 1998; Michon, 1993; Parasuraman et al., 1997; Seiler et al., 1998). In terms of warning reliability, research has shown that warnings with higher reliability increase driver trust of the warning systems, leading to a higher

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frequency of warning responses, and reduced collisions overall (Abe et al., 2009; Ben-Yaacov et al., 2002; Bliss and Acton, 2003; Bustamante et al., 2007; Chugh and Caird, 1999; Lees and Lee, 2007; Masuda et al., 2011; Sullivan et al., 2008).

The present study focused on speech warnings in connected vehicle systems. Compared to non-speech auditory warnings, speech warnings are more user-friendly and more widely applicable to connected vehicle systems in order to inform drivers of potential hazards ahead. People are able to easily understand and differentiate among speech warnings without specific training in warning memorization or recognition (Edworthy and Hards, 1999). Chang et al.(2008) found that speech warnings also led to better response performance than non-speech warnings with respect to hazard spatial information. Studies with a focus on speech warnings in the transportation systems indicated similar effects of warning timing and reliability on driver performance (Maltz and Shinar, 2007; Yan et al., 2014, 2015).

However, few existing studies have examined the timing and reliability of warnings in in-vehicle collision warning systems within the context of connected vehicle systems. Wan et al., (2016) and Winkler et al., (2016) have produced exceptional studies around the warning lead time in connected vehicle systems. Wan et al., (2016) specifically investigated driver performance while responding to speech warnings, with the warning lead time ranging from 0 s to 60 s. This study found that early warnings reduced collisions to a greater degree than late warnings. The lead time ranging from 4.5 s to 8 s produced the greatest safety benefits. Winkler et al., (2016) also evaluated drivers' perceived usefulness of visual warnings with lead time ranging from 6 s to 30 s. Still, neither study examined the effect of warning reliability on driver performance in connected vehicle systems.

Although research efforts have been dedicated to studying warning lead time and warning reliability separately, few studies have specifically investigated the interaction effects of warning lead time and warning reliability on driver behavior and performance. In his study, Abe and Richardson, (2006b) tested false and missed warnings in a collision warning system and found that drivers who experienced late warnings hesitated to respond to false warnings, while drivers who experienced early warnings tended to respond to false warnings and even missed warnings in critical situations due to delays in their response time. The data transmission range of connected vehicle systems was augmented by wireless communication technology, with which early warnings with longer lead times could be available. Drivers were provided with much more time to respond to hazards. Nevertheless, the number of to-be-transmitted data packages significantly increased due to the higher requirement of the transmission range. In turn, the number of missed warnings may have increased due to the higher load and possible congestion of the communication network of connected vehicle systems. Late warnings having a lower load on the communication network can be highly reliable, but can also delay a driver's response to the warnings and lead to potential collisions. Therefore, there is a trade-off between the warning lead time and warning reliability that must be considered in the design of connected vehicle systems. Driver assistant systems mainly depend on vehicle sensors to detect hazards, and the equilibrium of warning timing and warning reliability could be significantly different in connected vehicle systems. The interaction effect of these warning characteristics on driver performance must be quantified in order to achieve optimal effectiveness of connected vehicle systems.

In addition to warning lead time and warning reliability, speech warning style is another important variable in the design of speech warnings in connected vehicle systems. Uang and Hwang, (2003) suggested that notification style should be used for less critical messages and command style should be used for highly critical messages such as a collision warning. However, their study did not examine the impact of message style on driving performance in hazardous situations. The effect of message warning style on driving behavior was studied in a driving simulator experiment with command messages (e.g., "slow down") and notification messages (e.g., "icy road ahead") (Lee et al., 1999). Results suggested that command messages promoted greater compliance and longer compliance time than notification messages, but could reduce overall safety in terms of the number of crashes. Further research is needed to clarify the interaction effects between speech warning style and warning timing, and speech warning style and warning reliability.

This study aimed to investigate the effects of three speech warning parameters (warning lead time, warning reliability, and speech warning style) on driver behavior and performance in connected vehicle systems. A laboratory driving experiment was conducted to simulate the environment of a connected vehicle system with missed warnings due to a communication failure in the connected vehicle systems. Drivers' subjective evaluation of the warning effectiveness was also investigated and discussed.

2. Method

2.1. Participants

Thirty-two participants (22 males and 10 females) were recruited for the study. The inclusion criteria for the study were English proficiency and possessing a valid US driver's license. Participant ages ranged from 18 to 29 years with an average age of 20.8 (SD = 1.99) and an average lifetime driving experience of 36,718.8 miles ranging from 7500 to 105,000 miles (SD = 27,740.4). The average number of years of driving was 4.06 years (SD = 1.78) ranging from 1 to 10 years. The average annual mileage was 8984.4 miles (SD = 5307.5) ranging from 2500 to 22,500 miles. There was no statistically significant difference on the annual mileage between males drivers (*Mean* = 8750) and females drivers (*Mean* = 9250), F (1, 30) = 0.06, $p = .80$.

2.2. Apparatus

A STISIM® driving simulator (STISIMDRIVE M100 K, Systems Technology Inc., Hawthorne, CA) was used to present the simulated driving scenarios and the collision warnings. The simulator was equipped with a Logitech Driving Force steering wheel, a throttle pedal and a brake pedal (Logitech Inc., Fremont, CA). The STISIM simulator was installed on a Dell Workstation (Precision 490, Dual-Core Intel Xeon Processor 5130 2 GHz) with a 256 MB PCIe × 16 NVIDIA graphics card, Sound Blaster® X-Fi™ system, and Dell A225 Stereo System. Driving scenarios were presented on a 27-inch LCD with 1920 × 1200 pixel resolution.

The speech warnings were presented via a speaker in front of the participant with a digitized human female voice with a speech rate of 150 words per minute and a sound level of 70 dB. The background noise from the driving simulator with the engine running was presented through another speaker in front of drivers with a sound level of 55 dB on average.

2.3. Connected vehicle system setup

To set up a realistic design of the connected vehicle communication network in the human experiment and obtain the network reliability distribution, a network simulator called ns-3 ("ns-3 website,") was used to simulate the connected vehicle environment that combined the communication network, radio propagation (i.e., wireless radio path loss and shadowing) and vehicle mobility models. Among other open source and commercial simulation models, ns-3 was chosen because of its popularity in the Vehicular Ad-Hoc Network (VANET) literature (Hou et al., 2016). The parameters of the Dedicated Short-Range Communications (DSRC) were set as default values as shown in the Appendix. The safety application reliability used in the human experiment was calculated with package delivery ratio, transmission rate, and application tolerance time window. The results of the simulation

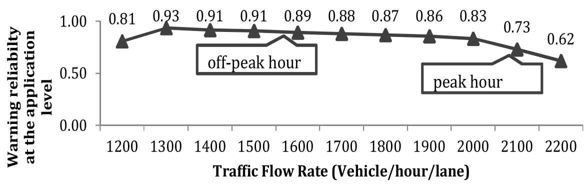


Fig. 1. The warning reliability at the application level with different traffic flow rates and transmission ranges.

indicated a change of the warning reliability at the safety application level (i.e., communication reliability) as a function of the traffic flow and the transmission range as shown in Fig. 1. The two levels of the communication reliability are 89% for off-peak hours and 73% for peak hours, respectively. These two levels of communication reliability as a key communication performance was input to the driving simulator experiment as the levels of warning reliability.

2.4. Experiment design

The experiment adopted a 2 × 2 × 2 mixed factorial design, with warning reliability as a between-subjects variable, and warning lead time and speech warning style as within-subjects variables. Warning reliability was calculated based on the parameters of the DSRC wireless communication and the average traffic flow for off-peak hours (89%) and peak hours (73%). The warning lead time was defined as the time-to-collision of the subject vehicle when the warning was issued. The time duration from a hazard was defined as the time when the hazard vehicle collided with the subject vehicle with no change in vehicle course, as either the speed and acceleration or the hazard no longer existed. Two levels of warning lead time (2.5 vs. 4.5 s) were tested in the experiment. The longer lead time (4.5 s) represented the optimal warning lead time that led to the greatest safety benefits (Wan et al., 2016). The shorter lead time (2.5 s) represented the widely-used, shortest lead time that allowed drivers to react to warnings before the collision (Yan et al., 2015). The speech warning style included notification warnings and command warnings. As it shown in Table 1, notification warnings included a description of the hazardous event (e.g., "Danger! Right front vehicle crossing your lane."), whereas the command warnings directed drivers' movement in order to avoid the hazardous event (e.g., "brake the vehicle").

The recruited thirty-two participants were evenly divided into two between-subjects experimental groups. Each group (16 participants) was assigned to a warning system with either an 89% or a 73% warning reliability. The levels of the warning lead times (2 levels) and the speech warning styles (2 levels) were combined to yield four within-subjects experimental conditions (i.e., Lead time = 2.5 s, Notification type; Lead time = 2.5 s, command type; Lead time = 4.5 s, Notification type; and Lead time = 4.5 s, Command type). The order of four within-subjects experimental conditions was counterbalanced in a balanced Latin square design resulting in four orders. Four participants were assigned to one of the four orders. Each participant experienced all four within-subjects experimental conditions and each experimental condition contained a sequence of four potential collision events that were randomly selected from the event list (See Table 1). In the high warning reliability condition, each participant experienced sixteen events in which two events had missed warnings (89% reliability). In the low warning reliability condition, each participant experienced sixteen events in which four events had missed warnings (73% reliability). The order of the missed warning was also randomized.

For each within-subjects experimental condition, drivers experienced a random selection of four events from the event list in Table 1. Each event was presented twice to each participant under different experimental conditions. The eight collision events were predesigned and programmed to represent the collision events supported by the connected vehicle technology (Najm et al., 2013). Depending on experimental conditions, drivers received a warning that was presented at either the 2.5 s or the 4.5 s lead time and with either the notification style or the command style of messaging. Within the missed warning condition, the hazard was presented in the driving scenario without any warnings.

2.5. Measures

The driving behavioral dependent variables examined in this study included warning response type, braking-onset reaction time, steering-onset reaction time, safety benefits measurements, and detailed braking process measurements. The warning response type included the following types: braking, steering to left, steering to right, braking and steering to left, braking and steering to right. The braking-onset reaction time was defined as time elapsed between the issued warning and the participant starting the braking response. The steering-onset reaction time was defined as time elapsed between the issued warning and the participant starting the steering response. The steering response criteria was defined as a minimum of ± 3° steering movement (Sullivan et al., 2008). The safety benefits measurements included the collision rate and the reduced velocity. The detailed braking process measurements included mean deceleration, maximum deceleration, accelerator-release reaction time, accelerator-to-brake transition time and brake-to-maximum transition time.

2.6. Procedure

Upon arriving, participants were asked to sign an informed consent form. Participants were then asked to provide demographic information. Next, participants were trained for the driving task by completing a training block. Participants were asked to operate the driving simulator with a speed limit of 45 mph and follow normal traffic laws, as if they were driving a vehicle in the real world. During this training session, participants were required to drive for a four-mile distance with normal road events to familiarize them with the driving environment and operation of the driving simulator.

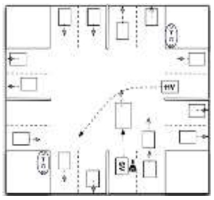
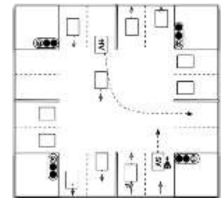
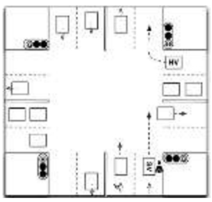
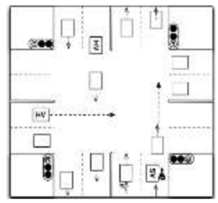
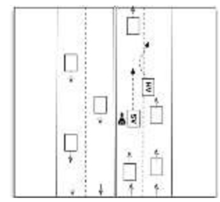
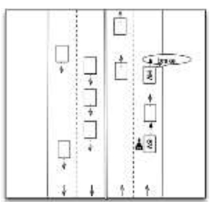
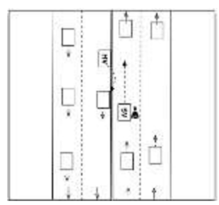
After the training block, participants completed the test block with sixteen events. The participants were informed that the vehicle they were driving was equipped with a warning system to help them identify potential hazards on the road, but the warning system was not perfect and might fail to alert them potential hazard event. To prevent drivers from anticipating hazard events in association with the emergence of messages, twenty normal messages (e.g., commercials, weather forecast, and news) were presented to drivers randomly during the test block with same speech rate and loudness level of the warning messages. An urban environment was simulated with a four-lane arterial road inclusive of two lanes in each direction, intersections with traffic lights and road signs, and running vehicles in each direction. The 45 mph speed limit signs were displayed 200 feet in front of the driver. All collision events were caused by the drivers of the hazard vehicle violating traffic regulations or exhibiting unsafe driving behaviors. To eliminate the learning effect, normal road events were designed and randomly assigned between two events, such as the emergence and departure of a lead vehicle. After experiencing each collision event, the driving scenario was paused. The participants were asked to evaluate the warning in terms of warning effectiveness, trust and acceptance of the warning, workload in response, and perceived hazard level of the event with 10-point scales.

3. Results

3.1. The interaction effects of warning reliability, speech warning style, and warning lead time on response type

Logistic regression analysis was conducted to determine the significant predictors of the response type of the initial responses and the

Table 1
The Event List with Corresponding Warning Messages.

Events 1-3			
Notification Warning	Danger. Right front vehicle crossing your lane	Danger. Left front vehicle entering your lane.	Danger. Oncoming vehicle crossing your lane
Command Warning	Brake the vehicle	Brake the vehicle	Brake the vehicle
Events 4-6			
Notification Warning	Danger. Ahead vehicle entering your lane.	Danger. Left front vehicle crossing your lane.	Danger. Ahead vehicle attempting merge.
Command Warning	Brake the vehicle	Brake the vehicle	Brake the vehicle
Events 7-8			
Notification Warning	Danger. Ahead vehicle stopping.	Danger. Oncoming vehicle swerving into your lane.	
Command Warning	Brake the vehicle	Brake the vehicle	

response type during the response process across all trials. The response type in the initial trial represented a driver's initial response to warnings in the connected vehicle systems. The response type across 16 trials indicated the likelihood of different responses to warnings in connected vehicle systems. Speech warning style, warning lead time, and warning system reliability were entered as predictors.

A logistic regression model was run with warning style, warning lead time, and warning reliability as inputs. The results of the likelihood ratio tests indicated that the warning style was the only significant predictor to the model, $\chi^2(4) = 11.31$, $p = .023$. However, the chi-square test of the modeling fitting showed the decrease in unexplained variance from the baseline model (39.89) to the final model (21.58) was not significant, *($\chi^2(12) = 18.30$, $p = .107$),* indicating that the final model does not explain a significant amount of the original variability. In other words, the final model is not a better fit than the original model. Therefore, a second logistic regression model as examined with the warning style inputted as the only predictor of the model. The chi-square test of the modeling fitting showed the decrease in unexplained variance from the baseline model to the final model was significant, *($\chi^2(4) = 10.78$, $p = .029$),* indicating that the final model explained a significant amount of the original variability. The Wald criterion in the likelihood ratio tests demonstrated that speech warning style significantly predicted the initial response type, ($\chi^2(4) = 10.78$, $p = .029$). As shown in Fig. 2, notification warnings led to a lower probability of braking response and a higher probability of braking and steering-to-right response. There was no "steering to right" or "braking and steering to right" response with the command warnings.

Tests of the logistic regression model of the response type in 16 trials during response process were statistically significant, indicating that the predictors, as a set, were able to predict the initial response type with marginal significance ($\chi^2(15) = 28.09$, $p = .021$). The Wald criterion demonstrated that speech warning style significantly predicted the response type, ($\chi^2(5) = 15.79$, $p = .007$). Similar to the results of response type in the initial trial, Fig. 3 outlines our suggestion

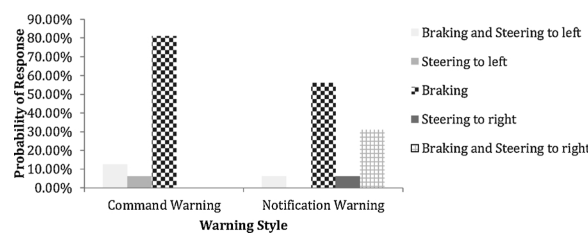


Fig. 2. The effect of speech warning style on response type in the initial trial.

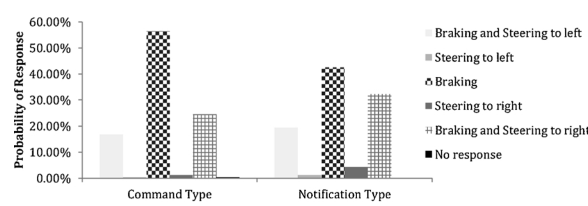


Fig. 3. The effect of speech warning style on response type in 16 trials.

that notification warnings led to a lower probability of braking response and a higher probability of braking and steering response compared with command warnings.

3.2. The interaction effects of warning reliability, speech warning style, and warning lead time on driving safety performance

A multivariate analysis of covariance (MANCOVA) was conducted to analyze the interaction effects of warning reliability, speech warning style, and warning lead time on driving performance. Initial speed was inputted in the model as a covariate. Collision rate, reduced velocity, braking onset reaction time and steering onset reaction time were inputted as dependent variables. The gender was initially analyzed as a

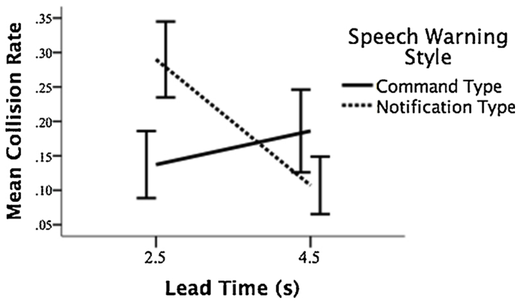


Fig. 4. The effects of speech warning style and warning lead time on collision rates.
(Error bars: +/- 1 SE)

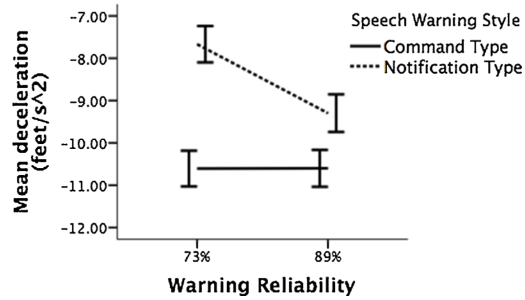


Fig. 5. The effects of warning system reliability and speech warning style on mean deceleration. (Error bars: +/- 1 SE).

covariate, however, there was no statistically significant difference between the gender groups on the combined dependent variable, F (4, 260) = 1.87, $p = .12$, *Wilks' Λ = .97*. Therefore, gender was not included in the refined MANCOVA analysis.

The results indicated that speech warning style had a significant main effect on reduced velocity, F(1, 210) = 6.64, $p = .001$. Command warnings reduced more velocity (55.10 feet/s) than notification warnings did (47.68 feet/s). Speech warning style also significantly affected braking onset reaction time, F(1, 210) = 5.31, $p = .022$, with command warnings leading to a shorter braking reaction time (0.82s) as compared to notification warnings (1.18s). Warning reliability had a significant main effect on reduced velocity, F(1, 210) = 6.25, $p = .013$. Unexpectedly, the warning system with a lower warning reliability (75%) reduced more velocity (54.55 feet/s) than the warning system with a higher warning reliability (90%) (48.23 feet/s). The lead time had a significant main effect on steering onset reaction time, F(1, 210) = 47.85, $p < .001$. Early warnings with a longer warning lead time led to a longer steering reaction time (3.43s) as compared to late warnings (1.75s).

Fig. 4 shows the significant interaction effect between speech warning style and warning lead time on collision rate, F(1, 210) = 4.50, $p = .035$. Fig. 4 shows the significant interaction effect between speech warning style and warning lead time on collision rate, F(1, 210) = 4.50, $p = .035$. The simple effect analysis indicated that command warnings resulted in a smaller collision rate compared to notification warnings when the warning lead time was 2.5s, F(1, 118) = 3.98, $p = .048$. However, no significant effect of speech warning style on collision rate was found when the warning lead time was 4.5s, F(1, 118) = 1.24, $p = .269$. This result suggested that the effect of speech warning style on collision rates was influenced by the warning lead time.

3.3. The interaction effects of warning reliability, speech warning style, and warning lead time on braking response profile

Since braking responses were involved in 92.5% of responses, an additional multivariate analysis of covariance (MANCOVA) was conducted to analyze the interaction effects of warning reliability, speech warning style, and warning lead time on driving braking performance. The initial speed was inputted in the model as the covariate. Collision rate, reduced velocity, warning onset to accelerator release reaction time, braking onset reaction time, and braking-to-maximum reaction time, mean deceleration, maximum deceleration were inputted as dependent variables.

Results indicated that the warning reliability had a marginally significant impact on mean deceleration, F(1, 503) = 3.84, $p = .05$. Speech warning style had a significant main effect on reduced velocity, F(1, 503) = 8.73, $p = .003$, and mean deceleration, F(1, 503) = 26.82, $p < .001$. Command warnings lowered overall velocity and led to higher mean deceleration levels, than did notification warnings. In terms of warning lead time, results showed that the lead time had a significant main effect on collision rates, F(1, 503) = 8.59, $p = .004$, and mean deceleration, F(1, 503) = 9.34, $p = .002$. Early warnings led to a lower collision rate and smaller mean deceleration than did late warnings.

As it shown in Fig. 5, speech warning style and warning reliability had a significant interaction effect on mean deceleration, F(1, 503) = 4.33, $p = .038$. For notification warnings, higher warning reliability (89%) led to a significantly larger deceleration than lower warning reliability (73%), F(1, 254) = 7.77, $p = .006$. Command warnings led to similar levels of deceleration across different levels of warning reliability, F(1, 254) = .00, $p = .991$. Moreover, warning style and warning lead time had a marginally significant interaction effect on accelerator-release reaction time, F(1, 503) = 3.66, $p = .056$.

3.4. The effect of warning reliability, speech warning style, and warning lead time on perceived warning effectiveness, trust, comprehensibility, and workload

Four analysis of variance (ANOVA) tests were run to examine the effect of warning reliability, warning style, and warning lead time on perceived warning effectiveness, trust to the warning system, warning comprehensibility and workload in warning response, respectively.

The results indicated that perceived warning effectiveness was significantly affected by speech warning style, F (1, 408) = 14.80, $p < .001$, and warning lead time, F (1, 408) = 9.07, $p = .003$. As shown in Fig. 6, a significant interaction effect between speech warning style and warning lead time on perceived warning effectiveness was also found, F (1, 408) = 4.29, $p = .039$. In particular, notification warnings were perceived as more effective than command warnings when warning lead time was 4.5s, F (1, 206) = 16.72, $p < .001$, whereas no such significant difference was found when warning lead time was 2.5s, F (1, 206) = 1.48, $p = .226$.

Warning reliability had a significant effect on trust, F (1, 407) = 10.15, $p = .002$, indicating that higher reliability warning systems led to higher levels of trust. As shown in Fig. 7, for a high reliable warning system, a significant interaction effect between speech warning style and warning lead time was found on driver trust of the

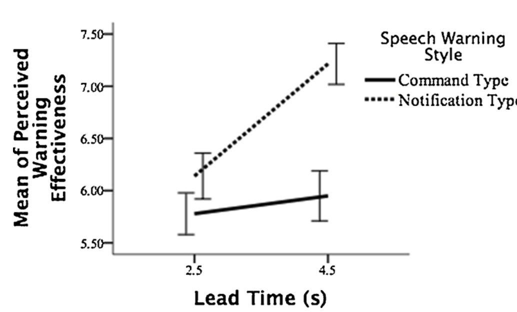


Fig. 6. The effect of speech warning style and warning lead time on perceived warning effectiveness (Error bars: +/- 1 SE).

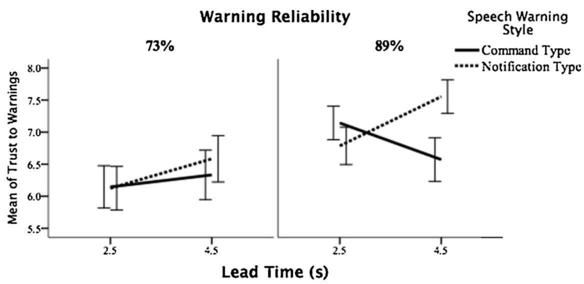


Fig. 7. The effect of warning reliability, speech warning style and warning lead time on drivers' trust of the warning system (Error bars: +/- 1 SE).

warning system, F (1, 220) = 5.32, p = .002, whereas no such interaction was found on driver trust when they encountered the warning system with lower reliability, F (1, 220) = 0.15, p = .703. More specifically, the notification warnings resulted in a higher trust level than command warnings when the lead time was longer (4.5s), F (1, 110) = 5.07, p = .024. However, there was no significant difference of trust between notification warnings and command warnings when the lead time was short (2.5s), F (1, 220) = 0.83, p = .365.

In terms of warning comprehensibility, warning reliability had a significant main effect on warning comprehensibility, F (1, 407) = 3.91, p = .049, indicating that higher reliability warnings led to higher level of comprehensibility of warnings than lower reliability warnings. Warning lead time also had a significant main effect on warning comprehensibility, F (1, 407) = 4.15, p = .042, indicating that longer warning lead time led to a higher level of comprehensibility of warnings than shorter warning lead time. As shown in Fig. 8, a significant interaction effect between speech warning style and warning reliability on warning comprehensibility was also found, F (1, 407) = 5.29, p = .022. In particular, drivers found command warnings were more easily comprehended in high warning reliability conditions than low reliability conditions, F (1, 206) = 0.06, p = .809.

All three warning parameters were found to significantly influenced drivers' workload in warning responses. The results indicated that lower reliable warnings led to a higher level of response workload than higher reliable warnings, F (1, 408) = 23.43, p < .001. Notification warnings led to a higher level of response workload then command warnings, F (1, 408) = 8.28, p = .004. Warnings with a shorter lead time to respond led to a higher level of response workload than warnings with a longer lead time, F (1, 408) = 29.85, p < .001. No interaction effects were found among the warning parameters on response workload.

4. Discussion

This study investigated the effects of warning style, warning lead time, and warning reliability on driver behavior in connected vehicle systems with missed warnings. These three warning parameters have been previously studied individually in collision warning systems. To the best of the researchers' knowledge, however, no existing studies have examined the interaction between these three warning parameters within the context of connected vehicle systems. The current study is the first study that examined the interaction effects of warning reliability, warning timing, and warning style on driver behavior and performance.

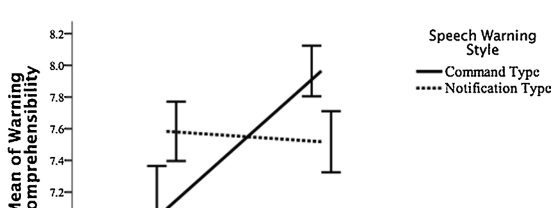


Fig. 8. The effect of the speech warning style and warning reliability on warning comprehensibility (Error bars: +/- 1 SE).

The results showed that speech warning styles and its interaction with warning lead time and warning reliability had important effects on driver safety benefits, braking response profile, and subjective rating of the warnings including perceived effectiveness, trust, and comprehensibility. This result provided important design considerations that different warning styles could be selected under different hazard and system conditions in the design of warning algorithm in connected vehicle systems. Moreover, this study constructed the warning reliability based on the performance of the communication network in peak hours and off-peak hours in connected vehicle systems, rather than testing the theoretical levels of the warning reliability.

An unexpected result was found in terms of the effect of warning reliability on reduced velocity. In particular, the results indicated that low reliable warnings reduced more velocity than highly reliable warnings. One possible explanation for this result could be that the drivers remained at a higher level of alertness in low reliable warning systems than they did in higher reliable warning systems.

The design of warning style and how it affects driver performance is important to be considered in the design of speech warnings, yet, was seldomly investigated in the literature. The previous study that investigated this parameter suggested that the command warnings undermined driver safety more than notification warnings did via a trend in the data of collision rate without a significant effect (Lee et al., 1999). However, the effect of warning style on driver performance under different levels of warning lead time or warning reliability was not investigated in Lee's study. The results of the present study suggested that command warnings led to a lower collision rate than notification warnings when warning lead time was shorter, whereas no significant difference was found when the warning lead time was longer. In terms of warning compliance, Lee's study (1999) found that command warnings promote greater compliance than notification warnings. However, the current study found that command warning lead to a greater compliance than notification warning in systems with a lower reliability, whereas no such difference was found significant in systems with a higher reliability. Finally, in terms of system trust, Lee's study found notification warnings led to a higher level of trust than command warnings, whereas the current study only found such difference under the condition with a longer lead time and a higher level of warning reliability. To summarize the results of the current study, the speech warning style influence driver behavior and their subjective rating of two warning style differently under different warning lead time and warning reliability.

To summarize, the findings of the current study have important implications for designing the warning algorithms in connected vehicle systems. Warnings with different styles can be selected based on different conditions of lead time and warning reliability. When a hazard is detected with only a short lead time before a potential collision or when a warning system, command warnings should be sent out to improve driver safety since they reduce more collisions and lead to a larger deceleration than notification warnings. However, when a hazard is detected with a longer lead time or a warning system has a higher warning reliability, notification warnings should be sent out since they do not limit drivers' response type, lead to higher trust and comprehensibility, and they were perceived as more effective than command warnings while keeping drivers safe as no difference was found on reduction in collisions and performance in braking response profiles. When a warning system has a lower warning reliability, it is better to ask drivers to rely more on themselves than the warning systems to respond to hazards. In this case, notification warnings should be sent out since both styles of warnings resulted in similar number of collisions, but notification warnings lead to a higher level of warning comprehensibility.

As well, this study was the first to investigate drivers' response types in collision warning systems. The experiment results suggested that drivers who received command warnings had a higher probability of giving single responses (i.e., braking-alone response), whereas drivers who received notification warnings had a relatively lower probability of giving braking-alone responses and a higher probability of giving dual responses (i.e., braking and steering response to either left or right direction). The purpose of exploring drivers' response type was ultimately to provide designers with information around drivers' decision-making processes under different warning settings, allowing designers to optimize the design of warnings based on driver behavior. In the next chapter, predictions relative to driver. response type will further assist in designing the algorithm for warning message selections.

Although this study was carefully prepared, there are still several limitations. First of all, the gender of participants was not intentionally balanced in this experiment with the sex ratio of 2.2. This is a reasonable sex ratio considering similar sex ratios in the national motor vehicle crashes were reported in 2016 (2.2) and in 2015 (2.3) based on the statistics published by National Highway Traffic Safety Administration (NHTSA, 2017, 2016). Secondly, the number of words in command warnings is less than that in the notification warnings. However, it is determined by the nature of the command warnings and notification warnings when such warnings are applied in the real design. Future study could be conducted to control the length of the warnings in order to better generalize the results of the current study. Finally, the failure type of warnings was limited to be missed warning in the current study. Existing study showed that missed warnings more affect reliance whereas false alarms more affected compliance (Chancey et al., 2017). However, considering there are already three independent variables designed in the current experiment to investigate the effects of key warning parameters, it is difficult to introduce the other warning failure type (false alarm) to compare the effects of false alarms and missed alarms on driver behavior. Therefore, future experiment is necessary to investigate the interaction effects among the same key warning parameters with the false alarm as the other warning failure type and compare the effects of warning failure types on driver behavior in connected vehicle systems.

5. Conclusion

This study investigated the effects of warning parameters on driver behavior and response performance in connected vehicle systems with missed warnings. The study found that notification warnings should be selected in longer warning lead time situations and higher warning reliability systems, as these systems resulted in higher safety benefits, better warning response performance, and highest subjective rating levels. Command warnings could be selected when the warning lead time is shorter, as they brought about more safety benefits for drivers overall. However, selection must be made with caution since command warnings may limit drivers' response type, lead to lower comprehensibility, and are perceived as less helpful than notification warnings in general.

Appendix

The simulated intersections contained two lanes in each of the four directions and the simulated straight road segments contained two lanes in each direction. In order to simplify the design on traffic signals, vehicles were assumed to be traveling in straight directions without taking left or right turns. Each lane was 12 feet in width and 1 mile in length. The speed limit was set to be 45 mph. In this simulation, vehicles were equipped with Dedicated Short Range Communications (DSRC) devices and were broadcasting the Basic Safety Message (BSM) as specified in IEEE 1609/WAVE as shown in Table A1. The DSRC runs on IEEE 802.11p protocol for the 5.9 GHz frequency range with a transmission range from 50 m to 500 m.

The simulation results were plotted in Fig. A1, showing the package delivery ratio (PDR) under different traffic flows and different transmission ranges. As expected, the PDR decreased due to congestion at the radio channels as the traffic flow rate increased. This result was in line with findings from existing studies regarding the relationship between PDR and traffic volume (Yin et al., 2014).

Table A1
The Dedicated Short Range Communications (DSRC) Parameters Setting.

Parameters	Values
Transmission power	20dBm
Packet size	200 bytes
Transmission rate	10 Hz
Transmission range	50-500 m
Application range	150 m (Bai and Krishnan, 2006)
Tolerance time window	0.3 s (Bai and Krishnan, 2006)
Traffic flow of peak hour (vehicle/hour/lane)	2100
Traffic flow of off-peak hour (vehicle/hour/lane)	1600

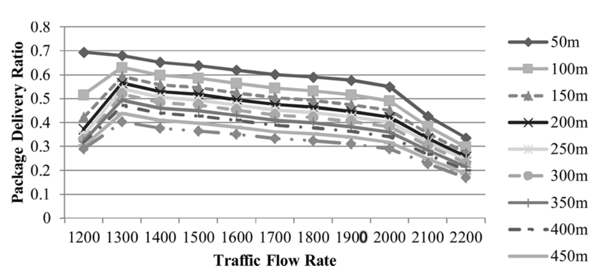


Fig. A1. The package delivery ratios with different traffic flow rates and transmission ranges.

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