Assessing the Effectiveness of Connected Vehicle Technologies based on Driving Simulator Experiments

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UNIVERSITY TRANSPORTATION CENTER

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Abstract

Connected vehicle technology is expected to reduce crashes and improve roadway safety overall despite its effect being dependent on the content of crash scenarios. The reason behind this is that the heterogeneity between crash scenarios may cause variation in a driver's perception and interpretation of the crash scenarios. Further, the heterogeneity may lead to different driver behaviors and evasive strategies. Consequently, both the benefits and influence of connected vehicle technology are affected.

This project aimed to identify the variation of the performance of connected vehicle technology between different crash scenarios. Specifically, two types of connected vehicle technologies, forward collision warning (FCW) technology and pedestrian-to-vehicle (P2V) technology, were tested in four rear-end crash scenarios and three pedestrian crash scenarios, respectively.

The results showed promising effectiveness of FCW and P2V technologies to reduce the possibility of a crash. Specifically, FCW reduced rear-end crashes by 56.6%-69.8%, and P2V reduced pedestrian crashes by 89.2%-97.2%.

More importantly, the results captured a significant variation in the performance of FCW and P2V between crash scenarios. In different scenarios, the technologies aroused different driver brake operations, and, consequently, the technologies achieved different safety benefits. In addition, the interaction effects between technologies and driver features were affected by crash scenarios. Age, gender, crash/citation experience, and driving experience were found to affect the warning effect in different scenarios.

This study has practical implications for the understanding of how heterogeneity of crash scenarios can affect connected vehicle technology.

1 Introduction

The rear-end crash and pedestrian crash are very common crash types that cause enormous socioeconomic loss every year. Rear-end crashes are the most frequent type of collision and make up around 29% of all crashes [1]. Pedestrian crashes, making up 19% of total traffic-related fatalities [2], often lead to severe injury or death. There is a great need to mitigate and prevent these two types of crashes.

The rear-end crash and pedestrian crash are expected to be mitigated or avoided by the emerging connected vehicle technology. Forward collision warning (FCW) and pedestrian-to-vehicle (P2V) warning are two connected vehicle technologies targeted at the rear-end crash and pedestrian crash, respectively. The FCW will alert a driver once he/she failed to keep a safe distance from the vehicle in front of them. The P2V warning will monitor and extrapolate the paths of the vehicle and pedestrian and will alert a driver if the system predicts an impending conflict.

In terms of FCW and P2V technologies, some research has been conducted in pursuit of an efficient warning algorithm design while considering human factors issues. For FCW, Lee et al. [3] utilized a high-fidelity driving simulator to evaluate the effect of both warning timing and situation severity on the efficacy of FCW. Meanwhile, by studying the change of driver response under different warning situations, they identified the mechanism of warning on driver behavior. Wu et al. [4] investigated the effectiveness of different warning displays in fog conditions. Their study demonstrated a significant interaction effect of the warning display methods with drivers' features, including age and gender. Abe et al. [5] concentrated on the driver's perception of warning timing and its influence on system trust. They showed that the warning had a greater impact on the rating of trust than improvements in braking behavior. In addition, Ho et al. [6] studied the warning content's influence on safety benefits. They proved that by adding the information on the direction of a potential collision, the driver responses to rear-end collision situations can be improved. As for P2V, Swanson et al. [7] summarized the typical pedestrian crash scenarios and connected the collision situations to the specific design requirement of P2V warning systems. In Europe, the majority of original equipment manufacturers (OEMs) were united in a project called PROSPECT to develop and test the next-generation pedestrian crash prevention system [8].

Given the current research, the effectiveness of FCW and P2V has been analyzed from multiple aspects and has achieved reliable results. However, few have studied the effectiveness of FCW and P2V considering the heterogeneity between imminent collision situations. Because a driver is very likely to behave and respond according to the features of that scenario itself, a warning may have different effects when it is moved from one scenario to another. Therefore, the purpose of this study was to investigate the effectiveness of FCW and P2V between collision scenarios of heterogeneity and to figure out how the warning interacts with other factors.

2 Experiment

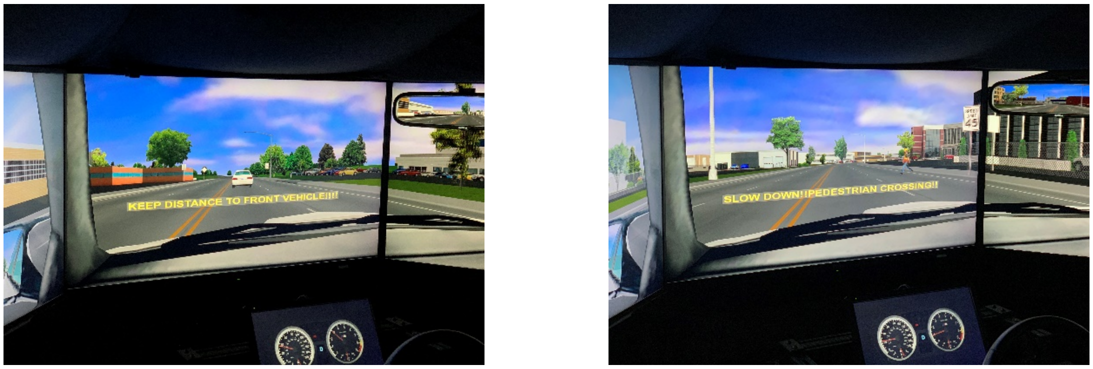
Two types of connected-vehicle technologies, FCW and P2V, were tested in the experiment. The experiment aimed to investigate the effect of FCW and P2V in different pre-crash scenarios. These pre-crash scenarios involved various trajectories, speeds, relative positions, timings of critical behavior, and other contributing factors, and consequently, a huge heterogeneity existed between scenarios. Facing such heterogeneity, drivers received different driving hints from the scenario. Meanwhile, their understandings of the current scenario and expectations of future development were different. Because of this, they may have behaved or adapted to the environment and prepare for the impending collision risk in a specific way, depending on the scenario. Working on both driver behavior and driving safety, the FCW and P2V may have different effects between pre-crash scenarios. This experiment aimed to capture such differences.

2.1 Participants

Initially, 56 participants who held a valid driver license were recruited for the experiment. The participants were divided into three groups: the young driver (18-24 years old), the working-aged driver (25-64 years old), and the elderly driver (>64 years old). Seven drivers had motion sickness and failed to finish any complete track in the experiment, so the data for these seven drivers were excluded. Some drivers also had motion sickness but managed to finish some tracks in the experiment, and the related data were kept for analysis.

2.2 Apparatus

Data was collected by the National Advanced Driving Simulator (NADS) miniSim. Three screens provide a 1300 forward field of view. A 2.1 channel sound system with a vibration transducer under the seat is utilized to simulate engine sound and vehicle vibration during driving. The warning was delivered with audio as well as a corresponding message displayed at the bottom of the middle screen (Figure 2.1). The FCW warning message was “Keep Distance!”, and the P2V warning message was “Slow Down! Pedestrian Crossing!”



(a) FCW warning (b) P2V warning

Figure 2.1 The display of warning icons (along with beep audio)

2.3 Experimental Design

The experiment was a within-subjects experiment. Warning type (i.e., with and without FCW/P2V warning) was used as the within variable. The advantage of a within-subjects experiment is that it controls extraneous participant variables and makes it easier to detect the relationships between the independent and dependent variables [9]. The experiment had four tracks, and the within-subjects design required that each participant experienced all four tracks. In each track, the participant was presented with one type of rear-end pre-crash scenario or one type of pedestrian pre-crash scenario or one type of both. In total, there were four types of rear-end pre-crash scenarios and three types of pedestrian pre-crash scenarios. These scenarios are introduced in detail in later sections. A participant experienced these pre-crash scenarios in both the with-warning and without-warning conditions. To prevent a participant from predicting the pre-crash scenario, multiple similar non-crash scenarios were presented between the pre-crash scenarios. To account for the carryover effect, all pre-crash scenarios and non-crash scenarios were counterbalanced with Latin sequence [9], and the order of each track presented to the participant was also counterbalanced.

2.3.1 Experiment 1: Rear-End Pre-Crash Scenarios

2.3.1.1 <u>Scenario Design</u>

The study defined four rear-end pre-crash scenarios, shown in Table 2.1. The four scenarios provided the driver with different driving hints regarding the leading vehicle's behavior. In the first scenario, the leading vehicle intends to go through an intersection; since the intersection has a yellow light, the following driver may acquire a hint that the leading vehicle may possibly stop for the yellow light. In the second scenario, the leading vehicle is traveling in the rightmost lane approaching an intersection with its right-turning signal on; the following driver may obtain a hint that the leading vehicle is likely to slow down. In the third and fourth scenarios, the leading vehicle is driving forward, and a hint to its behavior is not directly presented to the following driver; the following driver was told that the leading vehicle may make maneuvers as in the real world, alluding to the leading vehicle possibly braking suddenly. Upon receiving such hints to the leading vehicle's behavior, the following driver may expect a brake behavior of the leading vehicle and prepare for it. However, such preparation will be failed when the driver is distracted and unable to receive the leading vehicle's hint in time. This situation is quite common, and distraction is a major contributing factor to the rear-end crash. Consequently, a distraction task was given to the following driver in this simulator experiment. The distraction task was a cell phone operation that required the driver to type in numbers they saw on a cell phone screen. During the distraction task, the leading vehicle was programmed to brake suddenly until fully stopped or to slow down for turning; the following driver's behavior and vehicle kinematic movements.

Table 2.1 Rear-end pre-crash scenarios

Scenario ID	Location	Critical event	
		Following vehicle (participant)	Leading vehicle (scenario object)
1	Intersection with a yellow light in the front	Type in the numbers displayed on the phone screen; serve as a distraction to the participant	Intends to go through the intersection. However, a sudden hard brake is initiated and a full stop made before the parking line.
2	Intersection with a green light in the front		Travels in the rightmost lane and intends to turn right at the intersection. The turn signal is released. The vehicle will slow down to accommodate a required turning speed before it made the turn.
3	Arterial with a posted speed limit of 45 mph		Sudden hard brakes to full stop.
4	Freeway with a posted speed limit of 55 mph		

2.3.1.2 Warning Algorithms

In this study, the stop distance algorithm (SDA) was adopted to trigger the FCW warning. The SDA algorithm was commonly used in previous studies [5, 10, 11] for determining the timing of an FCW warning and has the form shown in Eq. 2.1. It has three parameters: reaction time (RT), following vehicle deceleration (a_f), and leading vehicle deceleration (a_l). Additionally, a distance R was added to the SDA to as an extra safety margin [3, 11]. In previous studies, the four parameters usually adopted values as follows: 1.25 s to 1.5 s for RT [3-5, 10]; 0.35 g (early warning) to 0.75 g (late warning) for a_f [3, 5, 10, 11]; 0.4 g to 0.85 g for a_l [3-5, 10-12]; and 2.0 m for R [3, 11]. In this study, the four parameters were set as 1.25 s, 0.65 g, 0.85 g, and 2.0 for RT, a_f, a_l, and R, respectively. Such parameter settings were expected to provide an early warning, which would be more efficient for avoiding a crash [3, 11].

$$\text{Warning Distance} = \frac{V_f^2}{2*a_f} - \frac{V_l^2}{2*a_l} + V_f * RT + R \qquad (2.1)$$

where V_f is the following vehicle speed, a_f is the following vehicle acceleration, V_l is the leading vehicle speed, a_l is the leading vehicle acceleration, RT is the reaction time, and R is the safety margin.

2.3.1.3 Dependent Variables

Two variables were used to quantify the safety benefit of the FCW warning, the collision rate, and the minimum modified time to collision (MTTC). The MTTC indicates the time to collision (TTC) if the vehicles continue to travel at their current speeds and accelerations from their current position, representing the safety margin available to the driver [1]. The lower the safety margin, the smaller the MTTC. The MTTC can be calculated by the following equation [4, 13]:

$$V_F t + \frac{1}{2} a_F t^2 \geq D + \frac{1}{2} a_L t^2 \tag{2.2}$$

where V_F is the following vehicle' speed (m/s), V_L is the leading vehicle' speed (m/s), a_F is the following vehicle's acceleration (m/s^2), a_L is the leading vehicle's acceleration (m/s^2), D is the initial relative distance (m), and t is the modified time to collision (s).

To characterize the driver's response, three measurements were used: throttle release time, brake reaction time, and brake transition time. Throttle release time measures how long it takes from the moment of the leading vehicle braking to the moment of the participant completely releasing the throttle. Throttle release time measures the acceleration change of the participant's vehicle and is included in the brake reaction time. The brake reaction time specifies the time between the onset of the leading vehicle's braking and the precise time when the participant begins to brake. The smaller the brake reaction time, the earlier the vehicle begins to decelerate. The brake transition time, or brake-to-maximum-brake time, measures the time spent by a driver to reach their own maximum deceleration after the initial depression of the brake pedal. A smaller brake transition time indicates a gentler brake.

2.3.2 Experiment 2: Pedestrian Pre-scenarios

2.3.2.1 Scenario Design

The study defined three pedestrian pre-crash scenarios, which are shown in Table 2.2. The scenarios were developed based on two pedestrian crash contributing factors: “unobservable pedestrian” and “unpredictable pedestrian”. The scenarios involving an “unobservable pedestrian” can happen with or without a marked crosswalk present; in the scenario, a pedestrian crossed the road from behind an obstruction such as bushes or parked cars, and they failed to be observed by passing drivers until the last moment before collision. In other scenarios, the pedestrian was unobservable due to other factors such as reduced light or darkness. Nevertheless, these factors played a similar role as the obstruction that prevented a driver from seeing the pedestrian before a collision. The scenario involving an “unpredictable pedestrian” usually happens somewhere without a marked crosswalk present. In the scenario, the pedestrian was well observed by the driver in advance; however, the pedestrian suddenly changed their posture and turned into the road. Since the participants may not expect the movements of the pedestrian, high conflict risk may present itself between the vehicle and the pedestrian. Consequently, three scenarios were designed, as shown in Table 2.2.

Table 2.2 Pedestrian pre-crash scenarios

Scenario ID	Location	Critical event
1	Arterial with a posted speed limit of 45 mph.	The participant is driving in the middle lane at an arterial segment without a marked pedestrian crosswalk. When the participant passes by a bush on the roadside, a scenario pedestrian suddenly darts out (10 mph) from behind the bush. The scenario pedestrian is unobservable before he darts out.
2	Arterial with a posted speed limit of 45 mph.	The participant is driving in the middle lane at an arterial segment without a marked pedestrian crosswalk. A scenario pedestrian is walking along the very near roadside when the participant approaches. The scenario pedestrian is visible to the participant. When the participant passes by the pedestrian, the

		pedestrian suddenly turns and darts into the road (10 mph).
3	Arterial with a posted speed limit of 45 mph.	The participant is driving in the rightmost lane at an arterial segment. A car is parked on the roadside near a marked crosswalk. When the participant passes the car, a scenario pedestrian enters (2.4 mph) the marked crosswalk from behind the parked car. The scenario pedestrian is unobservable before he walks out.

In Table 2.2, Scenario 1 and Scenario 3 are related to the contributing factor “unobservable pedestrian.” In Scenario 1, the scenario pedestrian darts out at somewhere without a marked crosswalk. In Scenario 3, the pedestrian walks into the marked crosswalk. In Scenario 1, the participant is driving in the middle lane, and in Scenario 3 the participant is driving in the rightmost lane. Scenario 2 is related to the contributing factor “unpredictable pedestrian.” As the participant drives in the middle lane and approaches the scenario pedestrian, the pedestrian can be always clearly observed. Before darting out, the pedestrian is walking along the roadside without showing obvious intentions of crossing the road. Moreover, there is no marked crosswalk present in Scenario 2.

The participant may receive different driving hints in the three scenarios. In Scenarios 1 and 3, although it may be hard to expect a pedestrian to appear from behind an obstruction, the marked crosswalk in Scenario 3 implies the participants should slow down because of the possibility of a pedestrian appearing. In Scenario 2, since the pedestrian is observable and in a moving status, an experienced driver would not ignore the pedestrian presence and would pay extra attention.

Some parameters related to the tracks were carefully considered. In all three tracks, the pedestrian was turned into the road when a participant was 2 s away from the conflicting point. This time distance was designed under a 45 mph speed limit and was expected to reproduce a scenario in which it would be difficult for a driver to stop in time if they did not slow down or pay additional attention to the pedestrian before they walked into the roadway. This time distance setting simulated real pedestrian crash cases related to Scenarios 1, 2, and 3. In these pedestrian crash cases, a common issue was that the pedestrian turned into the road at an extremely close distance to the passing driver. In these scenarios, the driver failed to brake in time or did not initiate the brake at all. Data from a much larger crash database, the General Estimates System (GES) and Fatality Analysis Reporting System (FARS), states that in 52% of all pedestrian crashes and 72% of fatal pedestrian crashes, drivers did not perform any avoidance maneuver [7]. All three tracks had a posted speed limit of 45 mph, and it was shown by a previous study [7] that this speed limit is associated with the highest frequency of fatal pedestrian crashes. For the warning timing, visual and audio messages were released 4 s prior to the pedestrian crossing. The warning 4 s in advance was expected to provide an early warning allowing drivers enough time to brake.

2.3.2.2 Dependent Variables

To quantify the safety benefit of the P2V warning, the collision rate, impact velocity, and post-encroachment time (PET) were used. The PET is the time difference between the moment a conflict road user leaves the area of a potential collision and the moment of arrival of the other conflict road user. The PET is often used in the vehicle-pedestrian conflict scenario as a measurement of safety margin [14, 15]. The larger the PET, the larger the safety margin.

To characterize the driver's response, the decomposed brake operation time and the braking profile were used. The decomposed brake operation time includes the throttle release time, brake reaction time, and brake-to-maximum-brake transition time. The braking profile includes the mean acceleration and maximum acceleration. All three variables were measured from the moment the pedestrian turned into the road, i.e., when the pedestrian was visible to the driver, to the moment the distance between pedestrian and vehicle was at its minimum.

2.3.3 Interaction Effect Variables

The driver features were analyzed for their interaction effects with the warning. The driver features include demographic features (A) and driving experience (B). The demographic features include age (A1), gender (A2), and education level (A3). Age is split into three categories of young, working-aged, and elderly. Gender and education level are dichotomous variables. Education level is divided by below or not below the bachelor's degree. Driving experience contain three variables: experienced crash/citation in the last five years or not (B1), years of having a valid driving license (B2), and how frequently the participant drives in general (B3). The variables B2 and B3 were further integrated to define an experienced driver. With the integration of variables B2 and B3, if a participant has possessed a driver license for many years (i.e., a larger B2) and he/she uses the vehicle more frequently (i.e., a larger B3), the participant is more likely to be an experienced driver. To integrate these variables, a clustering process was conducted to categorize the participants of various pairs of characters (B2, B3) into two groups.

The clustering process took two steps. In the first step, the dissimilarity matrix between participant features was calculated. Because B2 was collected as a continuous variable and B3 was collected as a categorical variable, the Gower distance [16] was used for such mixed-type data. The Gower distance measures the similarity between i and j by calculating the weighted average score over all possible comparisons [16]:

$$S_{ij} = \sum_{k=1}^{v} S_{ijk} \,/ \sum_{k=1}^{v} \delta_{ijk}. \tag{2.3}$$

where k is the kth feature, and $\sum_{k=1}^{v} \delta_{ijk} = \mathrm{v}$ is the total number of features when all comparisons are available.

For qualitative features, $S_{ijk} = 1$ if the two individuals i and j are consistent in the Kth feature; otherwise, it is zero. For quantitative features, $S_{ijk} = 1 - \left|x_i - x_j\right| / R_k$ and R_k is the range of feature k.

In the second step, based on the dissimilarity matrix, the agglomerative clustering algorithm was used to categorize the participants. Agglomerative clustering is a “bottom-up” approach in which each observation starts from its own cluster, then merges with other clusters from the bottom to the upper hierarchy [17]. In this study, in order to keep enough samples in each category, only two levels of an experienced driver (i.e., yes or no) were decided. Because the number of clusters is small, the agglomerative clustering algorithm has its priority [17].

Figure 2.2 shows the clustering results. The non-experienced drivers had an average of 8.5 years of holding a driving license and had less than three trips per day. The experienced drivers had an average 11.7 years of holding a driving license and had more than three trips per day.

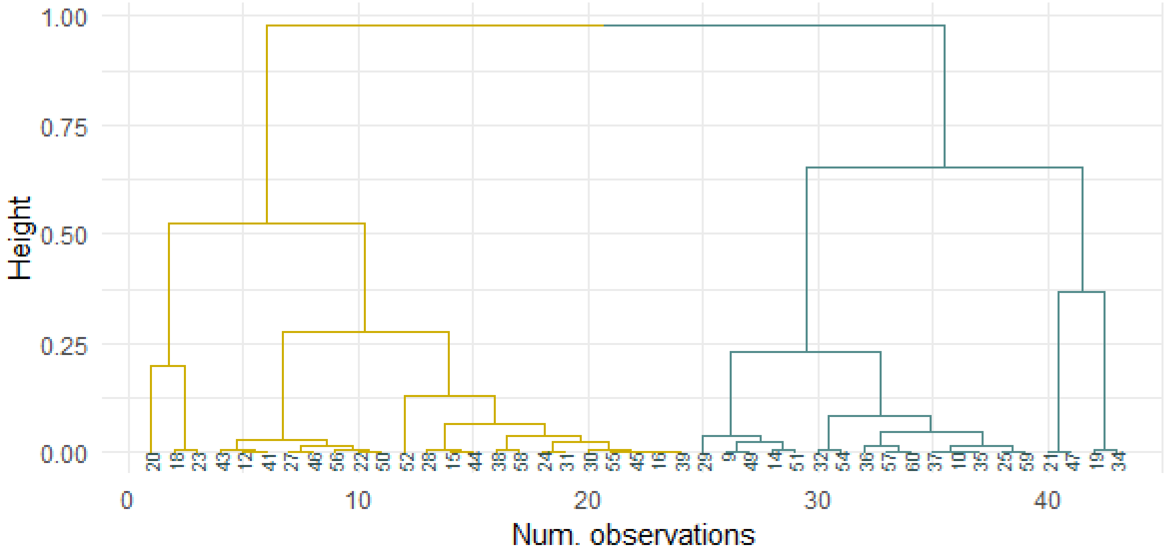


Figure 2.2 Two clusters of experienced drivers and non-experienced drivers

2.4 Procedure

Upon arriving at the driving simulator lab, each participant completed a consent form and demographic survey. The participants were told to drive as they normally would and that they could quit the experiment at any time they experienced motion sickness. Before starting the formal experiments, each participant was given a 10-minute practice drive to get used to the control of the simulator. In the practice drive, each participant was told that the leading vehicle may brake and to only use the brake (not the steering wheel) to stop behind the leading vehicle. Also, the participant was told to yield to the crossing pedestrian and to again only use the brake to come to a stop. In the practice driving, the participants were asked to type in numbers displayed on the phone. The aim was to let the participant become familiar with the phone operation as a distraction task.

Following the practice drive, each participant experienced the four tracks in an order based on Latin sequence. In each track, a participant experienced one rear-end pre-crash scenario and one pedestrian pre-crash scenario. The order of the pre-crash scenarios was presented to each participant based on Latin sequence. For the rear-end pre-crash scenario, a vehicle-following process was arranged in which the leading vehicle kept a fixed headway with the following driver before the scenario was activated. In this study, the headway was set as 2.5 s. A headway of 1.7-2.5 s was commonly adopted in previous studies [3, 5, 10, 12]. In the rear-end pre-crash scenario, a visual message was first prompted, which asked the participant to operate on the phone. The message allowed 5 s for the participant to prepare and immerse themselves in the task. Then, the leading vehicle conducted a hard brake at -8 m/s2. For both rear-end and pedestrian pre-crash scenarios, multiple similar scenarios without leading vehicle brake and pedestrian crossing were arranged in the track. Therefore, a participant was hard-pressed to associate the occurrence of critical events with specific scenario configurations.

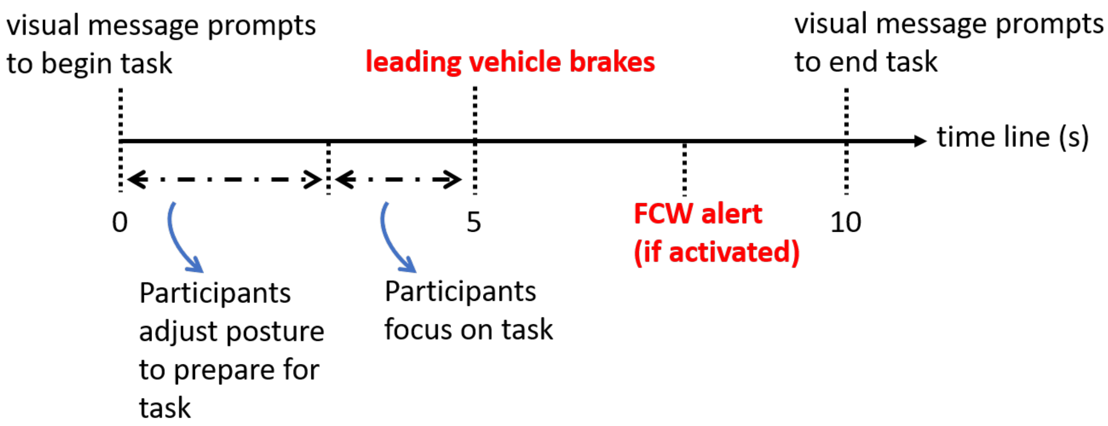


Figure 2.3 The process of the distraction task presented to a participant

Between each track, the participant had a resting period of 5-10 minutes. Overall, the experiment lasted for about one and a half hours. After the experiment, participants were required to evaluate both the fidelity of the simulator and the usefulness of warning. 82% of participants thought the scenarios were realistic. For P2V warning, 91% of participants thought the warning helped them in the pre-crash scenarios, and 51% of participants thought the warning was very helpful (the highest rate). For FCW warning, 93% of participants thought the warning helped them in the pre-crash scenarios, and 36% of participants thought the warning was very helpful (the highest rate). Methods

The within-subjects repeated-measurement ANOVA analysis was used in the study. This analysis approach was conducted by the SAS correlated errors model (SAS PROC MIXED procedure). A correlated errors model was developed by adding a random effect from individual drivers. The correlated errors model has the form shown below [18]:

$$Y_{ij} = \mu + \tau_i + \tau_i * \alpha_i + B_j + \varepsilon_{ij} \quad (2.4)$$

where Y_{ij} is the response (i.e., PET) measured with specific warning type (with/without warning), μ is the overall mean, τ is the mean effect of the warning type, $\tau * \alpha$ is the interaction effect between warning type and other variables, B is the random subject effect, ε is the error, and B~N (0,σ_B^2), ε ~N (0,σ_ε^2).

3 Results

3.1 FCW Warning for Rear-End Pre-Crash Scenarios

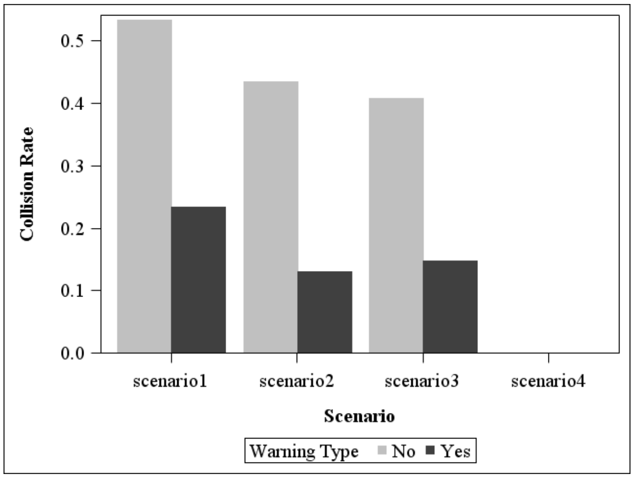
For rear-end pre-crash scenarios, the distraction work was not given to the elderly drivers (>64 years old) because they either were unable to answer the question on the phone due to eyesight issues or became very motion sick after engaging in the distraction work. Because of this, elderly drivers were excluded from the analysis of rear-end scenarios. Finally, after further filtering out participants with motion sickness and other invalid samples, the total valid sample size came to 46 participants. The valid participants were between the ages of 18 and 64 years (mean: 27.5 years old), comprised of 21 young drivers and 25 working-aged drivers.

3.1.1 Safety Benefit of FCW Warning

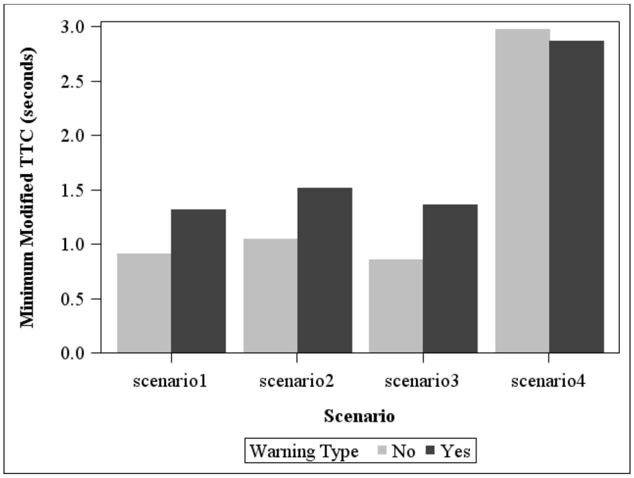
3.1.1.1 Main Effects

Figure 3.1 shows the change of collision rate and MMTTC between the no-warning situation and warning situation. The FCW warning showed a positive effect on the collision rate and MMTTC. The FCW warning significantly reduced the collision rate in Scenarios 1, 2, and 3: in Scenario 1, the collision rate was reduced from 0.53 to 0.23 (-56.6%; P-value=0.0046); in Scenario 2, the collision rate was reduced from 0.43 to 0.13 (-69.8%; P-value=0.0159); in Scenario 3, the collision rate was reduced from 0.41 to 0.15 (-63.4%; P-value=0.0165). In Scenario 4, a collision did not occur in either the no-warning situation or the warning situation, so the safety benefit of FCW warning on collision reduction was not directly observed. The MMTTC also demonstrated the safety benefits of FCW warning in Scenarios 1, 2, and 3: in Scenario 1, the MMTTC increased from 0.91 s to 1.31 s (P-value=0.0524); in Scenario 2, the MMTTC increased from 1.05 s to 1.51 s (P-value=0.0434); in Scenario 3, the MMTTC increased from 0.89 s to 1.36 s

(P-value=0.0130). In Scenario 4, the MMTTC didn't change significantly after the warning was provided (P-value=0.6521).



(a) Collision rate

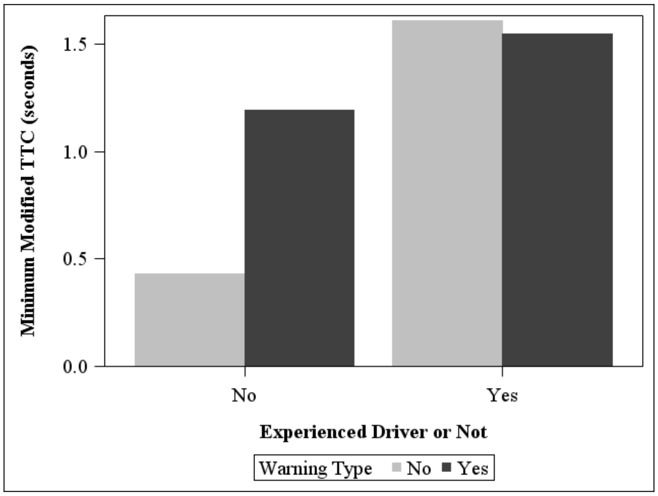


(b) Minimum modified TTC

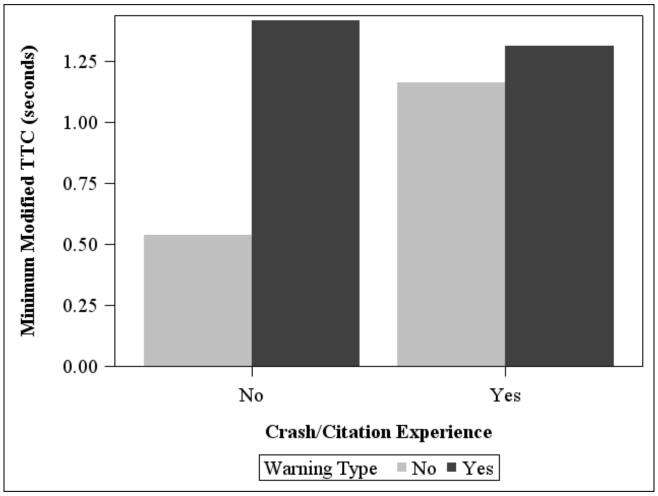
Figure 3.1 Safety benefit of FCW warning in different rear-end pre-crash scenarios

3.1.1.2 Interaction Effects

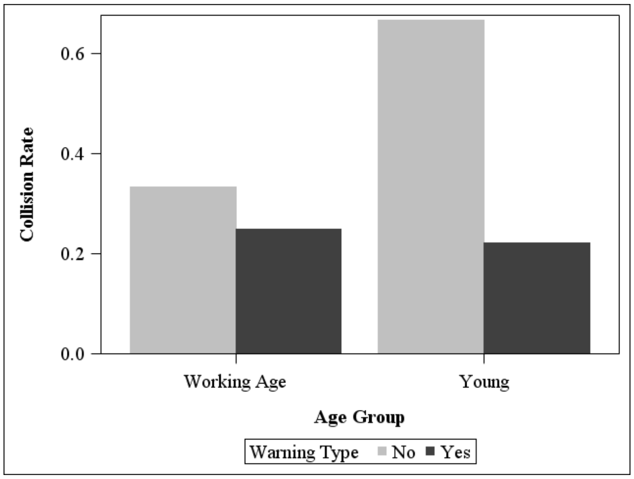
Table 3.1 shows driver features that affected the FCW warning's safety benefits. Driving experience of the participant was found to affect the FCW warning's effect on MMTTC in Scenario 1 (P-value=0.055). The crash/citation experience of a participant interacted with the warning on MMTTC in Scenario 3 (P-value=0.044). Figure 3.2 shows the FCW warning's effect on participants who hold different levels of driving experience and crash/citation experience, respectively. Figure 3.2 (a) shows that in Scenario 1, the warning was mainly effective on non-experienced drivers: after providing the warning, the MMTTC increased from 0.43 s to 1.19 s (P-value=0.0085). Figure 3.2 (b) shows that in Scenario 3, the warning significantly improved the safety margin of drivers who had no prior crash or citation experience: for these drivers, the MMTTC increased from 0.54 s to 1.42 s (P-value=0.0014). Figure 3.2 (c) and (d) show that in Scenario 1, the warning significantly reduced the collision rate for young drivers (P-value=0.069) and non-experienced drivers (P-value=0.044). Figure 3.2 (e) shows that in Scenario 3, the warning significantly reduced the collision rate for drivers who didn't have prior crash/citation experience (P-value=0.052).



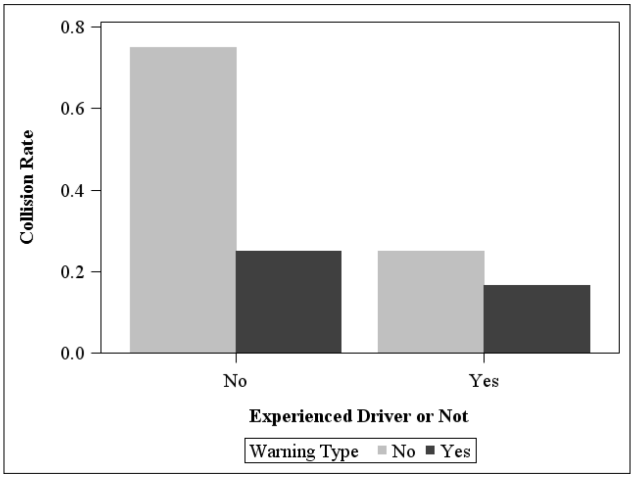
(a) Scenario 1 - MMTTC-driving experience



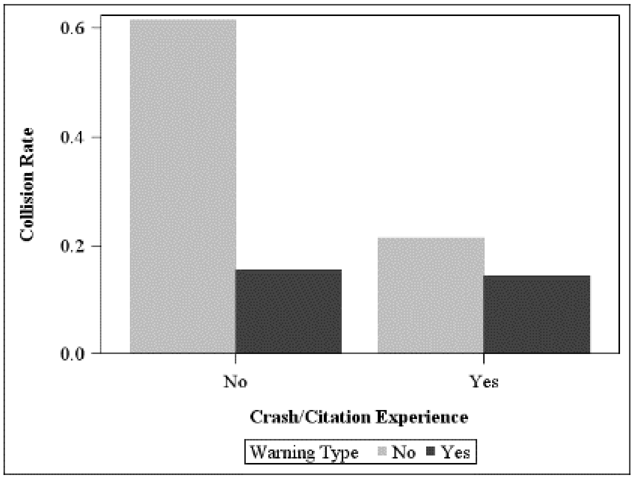
(b) Scenario 3 - MMTTC-crash/citation experience



(c) Scenario 1 - collision rate-age group



(d) Scenario 1 - collision rate-driving experience



(e) Scenario 3 - collision rate-crash/citation experience

Figure 3.2 Interaction effects of FCW warning on safety benefits

As for the effect on the collision rate, Table 3.1 shows that the FCW warning interacted with age (P-value=0.069) and driving experience (P-value=0.044) in Scenario 1, and the FCW warning was affected by crash/citation experience (P-value=0.052) in Scenario 3. Figures 5 (c), (d), and (e) show that the effect of FCW warning varies between different levels of age, driving experience, and crash/citation experience. Figures 5 (c) and (d) show that in Scenario 1, the warning was particularly useful for young drivers and non-experienced drivers, reducing the collision rate from 0.67 to 0.22 for young drivers (P-value=0.001), and from 0.75 to 0.25 for non-experienced drivers (P-value=0.0006). Figure 5 (e) shows that in Scenario 3, the warning had much higher collision reduction for drivers who had no crash or citation experience before: for these drivers, the collision rate was increased from 0.62 to 0.15 (P-value=0.0026).

The gender and education level did not display any significant effect on safety benefits of FCW warning.

Table 3.1 The P-value for interaction terms of FCW warning effects on safety benefits

MMTTC					
Scenario	Interaction effect: warning*driver features				
	age	gender	education level	crash/citation experience	driving experience
1	0.254	0.156	0.987	0.62	**0.055***
2	0.803	0.123	0.554	0.515	0.523
3	0.675	0.945	0.442	**0.044****	0.622
4	0.244	0.310	0.602	0.827	0.866
Collision rate					
Scenario	Interaction effect: warning*driver features				
	age	gender	education level	crash/citation experience	driving experience
1	**0.069***	0.836	0.366	0.314	**0.044****
2	0.372	0.225	0.271	0.802	0.523
3	0.954	0.937	0.295	**0.052***	0.665
4[a]	N/A				

a. In track 4 no collision occurred.

** significant at 0.05 level

* significant at 0.10 level

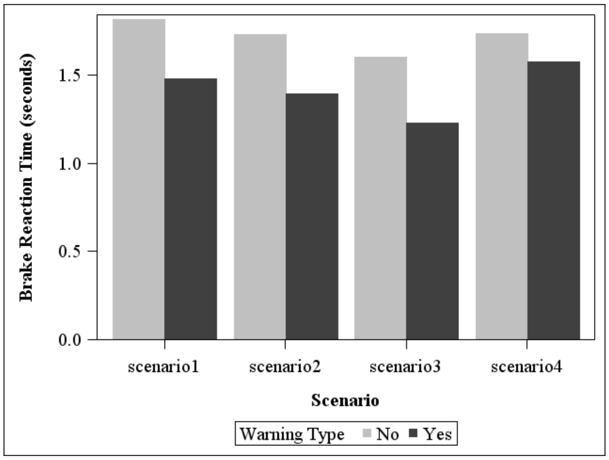
3.1.2 Response Behavior under FCW Warning

3.1.2.1 Main Effects

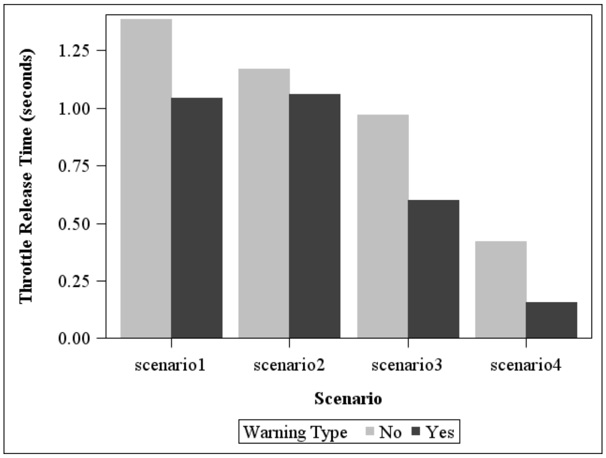
The safety benefits of FCW warning were induced by the change in throttle and brake processes by the driver. The response process can be divided into two sections: (a) from the onset of the leading vehicle's brake to when the following driver begins to brake, denoted by brake reaction time, and (b) from the time the following driver initiates braking to when they reach maximum braking, denoted by brake transition time. The brake reaction time includes the period from when the leading vehicle starts to brake to the following driver releasing the throttle: this period is denoted by throttle release time.

The reduction of brake reaction time or brake transition time can achieve a safety benefit.

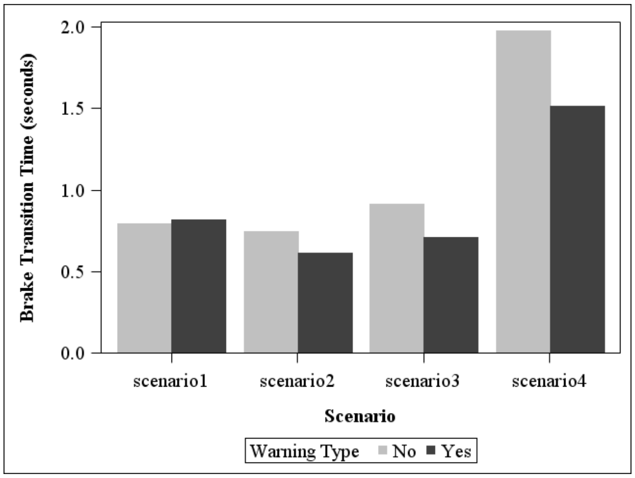
Figure 3.3 shows that the FCW warning significantly reduced the brake reaction time and throttle to release time in Scenarios 1 and 3. In Scenario 1, the brake reaction time was reduced from 1.81 s to 1.49 s (P-value=0.014), and the throttle release time was reduced from 1.39 s to 1.06 s (P-value=0.070). In Scenario 3, the brake reaction time was reduced from 1.60 s to 1.23 s (P-value=0.012), and the throttle release time was reduced from 0.97 s to 0.60 s (P-value=0.016). The FCW warning also reduced the brake reaction time in Scenario 2 from 1.73 s to 1.39 s (P-value=0.038). The throttle release time in Scenario 2 was not significantly changed by the FCW warning (P-value=0.624). Neither brake reaction time nor throttle to release time were significantly affected by the FCW warning in Scenario 4 (P-value>0.1). Figure 3.3 also shows that the brake transition time was similar between the warning condition and no-warning condition across all four scenarios: in four scenarios, no effect of FCW warning on brake transition time was found (P-value>0.1).



(a) Brake reaction time in different scenarios



(b) Throttle release time in different scenarios



(c) Brake transition time in different scenarios

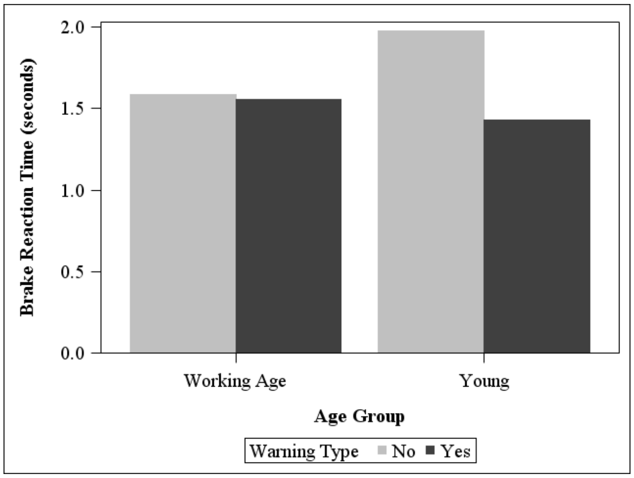
Figure 3.3 Response process: throttle and brake operation

3.1.2.2 Interaction Effects

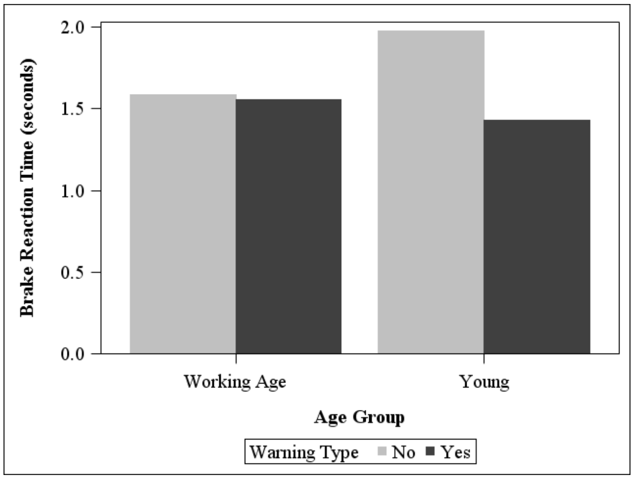
Table 3.2 shows driver features that affected the FCW warning's effect on response behaviors. For brake reaction time, both the age (P-value=0.044) and driving experience (P-value=0.0076) were found to affect the warning's effect in Scenario 1. In Scenario 1, Figure 3.4(a) shows that the warning worked for young drivers: after providing the warning, the brake reaction time was reduced from 1.97 s to 1.44 s (P-value=0.0018). Meanwhile, in Scenario 1, Figure 3.4(b) shows that the warning also worked well for non-experienced drivers: for these drivers, the warning significantly reduced the brake reaction time from 2.06 s to 1.51 s (P-value=0.0009).

For brake transition time, the crash/citation experience (P-value=0.016) was found to interact with the warning in Scenario 1. Figure 3.4(c) shows that the warning in Scenario 1 increased the brake transition time for drivers who had no crash/citation before: the difference was from 0.56 s to 0.92 s and was statistically significant (P-value=0.056). A decrease of brake transition time was observed for drivers having crash/citation before, the decrease was not significant (P-value=0.117). In addition, the driving experience (P-value=0.032) was also found to affect the warning effect in Scenario 3. Figure 3.4(d) shows that the warning made the non-experienced driver brake harder than in the non-warning situation. By warning the driver, the brake transition time was reduced from 1.11 s to 0.58 s (P-value=0.029); however, the warning effect on experienced driver was not significant (P-value=0.275).

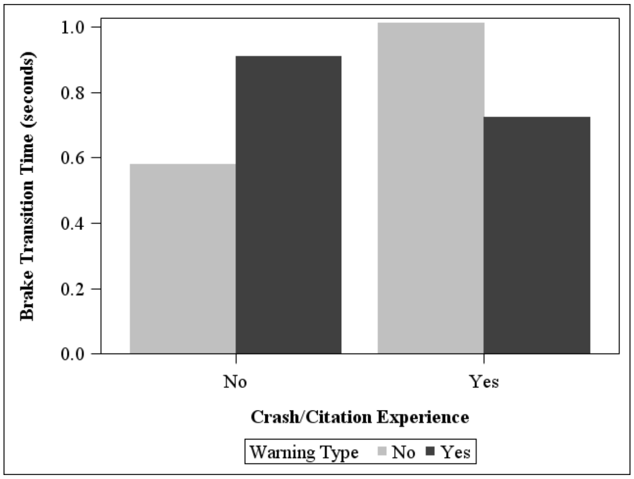
For throttle to release time, the FCW warning only had the main effect. There is no evidence that gender and education level significantly affected the FCW warning in terms of response behavior.



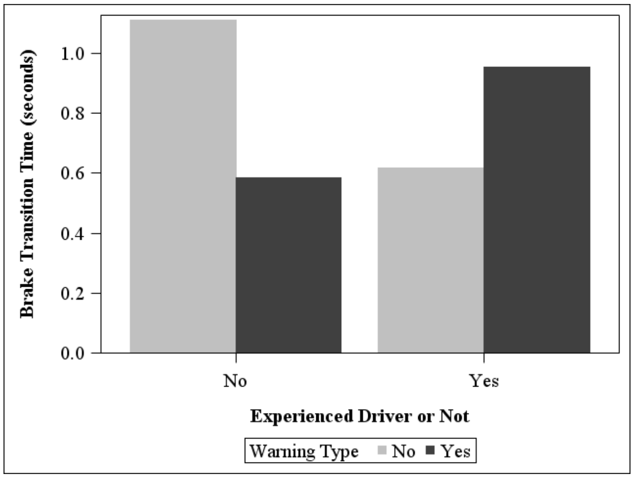
(a) Scenario 1 - brake reaction time and age group



(b) Scenario 1 - brake reaction time and driving experience



(c) Scenario 1 - brake transition time and crash/citation experience



(d) Scenario 3 - brake transition time and driving experience

Figure 3.4 Interaction effects of FCW warning on response behavior

Table 3.2 The P-value for interaction terms of FCW warning on response behavior

Throttle release time					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.622	0.121	0.720	0.704	0.139
2	0.582	0.293	0.652	0.195	0.538
3	0.253	0.818	0.470	0.979	0.531
4	0.127	0.579	0.338	0.686	0.189
Brake reaction time					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	**0.044****	0.267	0.598	0.137	**0.008****
2	0.326	0.418	0.956	0.215	0.226
3	0.207	0.984	0.241	0.912	0.348
4	0.154	0.634	0.375	0.157	0.670
Brake transition time					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.360	0.287	**0.016****	0.251	0.233
2	0.153	0.206	0.753	0.494	0.802
3	0.542	0.830	0.797	0.322	**0.032****
4	0.804	0.367	0.410	0.450	0.647

** significant at 0.05 level

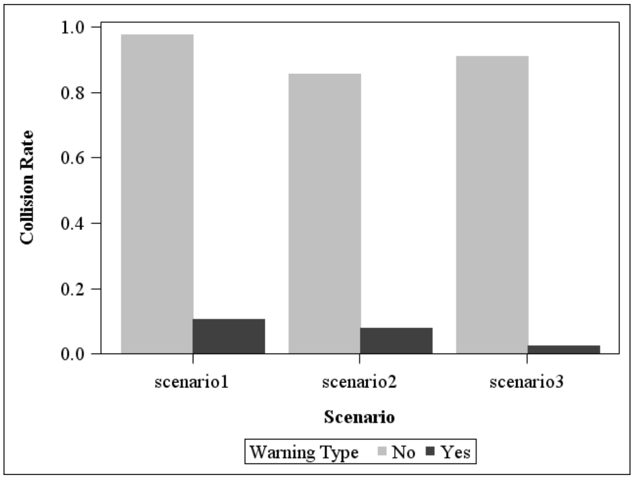
* significant at 0.10 level

3.2 P2V Warning for Pedestrian Pre-Crash Scenarios

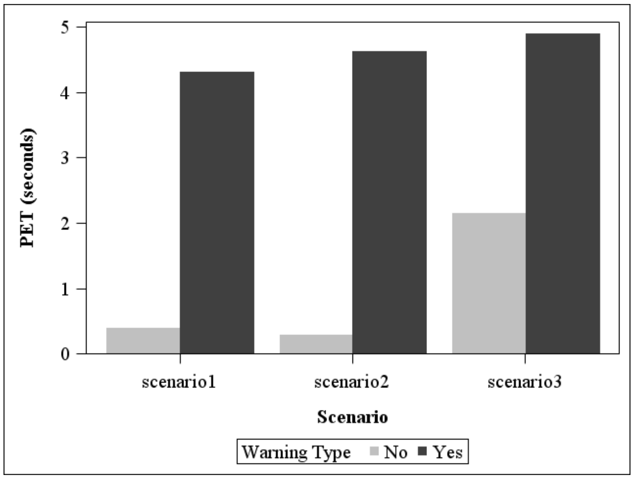
3.2.1 *Safety Benefit of P2V Warning*

Figure 3.5 shows the change of collision rate and PET in the no-warning and warning conditions. Compared with the no-warning condition in which drivers had more difficulty stopping the vehicle, the P2V warning significantly reduced the collisions (P-value<0.0001): in Scenarios 1, 2, and 3, the collision rate was reduced from 97.67% to 10.56% (-89.2%), 85.71% to 7.74% (-91.0%), and 91.14% to 2.58% (-97.2), respectively. The PET also significantly increased, from 0.40 s to 4.34 s in Scenario 1, 0.28 s to 4.62 s in Scenario 2, and 2.15 s to 4.90 s in Scenario 3.

Table 3.3 shows the interaction effect of P2V warning on the collision rate and PET in each scenario. For the collision rate, only the crash/citation experience was found to interact with the warning in Scenario 1 (P-value=0.023). Figure 3.6(a) shows that the P2V warning reduced all collisions for drivers who had crash/citation experience in the past five years and only reduced 80% of collisions for drivers who didn't have crash/citation experience in the past five years.



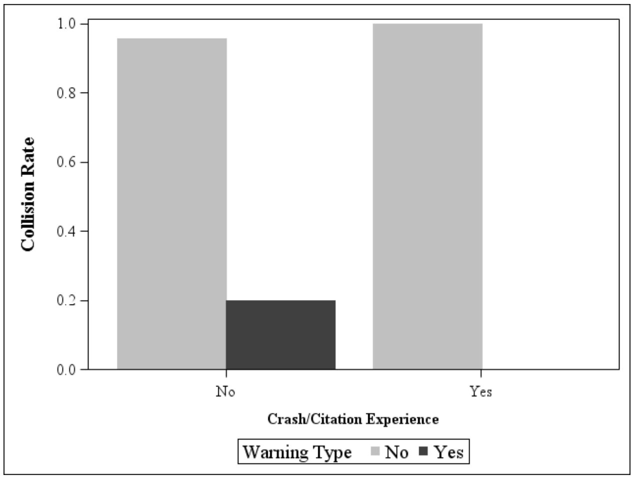
(a) Collision rate in different scenarios



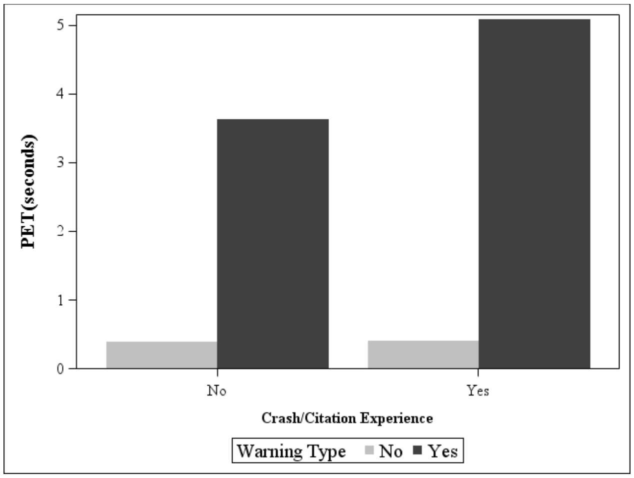
(b)PET in different scenarios

Figure 3.5 Safety benefit of P2V warning in different track scenarios.

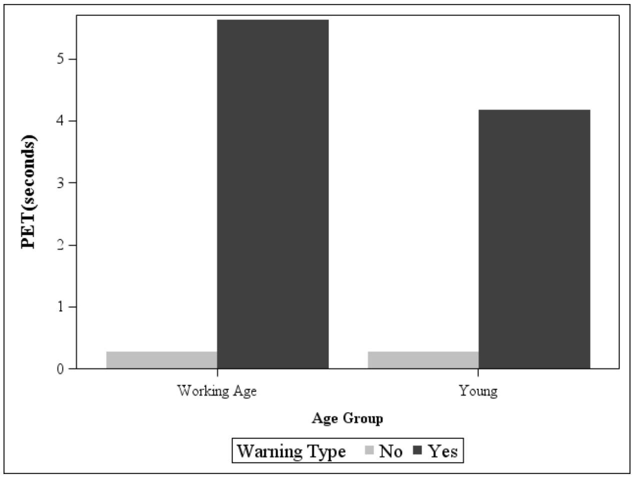
PET was found to interact with crash/citation experience and age. Specifically, in Scenario 1, the P2V warning interacted with crash/citation experience (P-value=0.031). Figure 3.6 (b) shows that for drivers who had crash/citation in the past five years, the warning increased the PET from 0.40 s to 5.08 s. For drivers who did not have crash/citation in the past five years, the PET increased from 0.38 s to 3.66 s. In Scenario 2, the P2V warning interacted with age (P-value=0.082). Figure 3.6 (c) shows that for working-aged drivers, the PET increased from 0.28 s to 5.69 s. For young drivers, the PET increased from 0.27 s to 4.22 s. Similar to Scenario 2, in Scenario 3, age affected the P2V warning (P-value=0.035). Figure 3.6(d) shows that the warning increased PET from 2.01 s to 5.80 s for working-aged drivers and from 2.24 s to 4.42 s for young drivers.



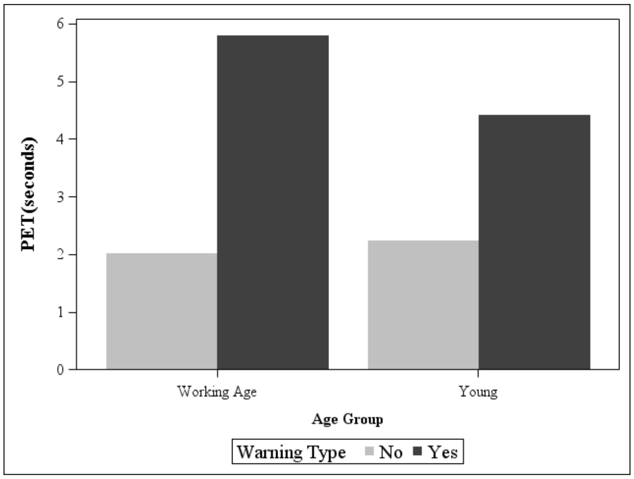
(a) Scenario 1 - collision rate and crash/citation experience



(b) Scenario 1 - PET and crash/citation experience



(c) Scenario 2 - PET and age group



(d) Scenario 3 - PET and age group

Figure 3.6 The interaction effects of P2V warning on safety benefits

Table 3.3 The P-value for interaction terms of P2V warning effects on safety benefits

Collision rate					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.118	0.781	**0.023****	0.766	0.482
2	0.285	0.525	0.171	0.372	0.177
3	0.226	0.646	0.890	0.878	0.836
PET					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.834	0.208	**0.031****	0.848	0.194
2	**0.082***	0.344	0.197	0.413	0.483
3	**0.035****	0.766	0.750	0.205	0.456

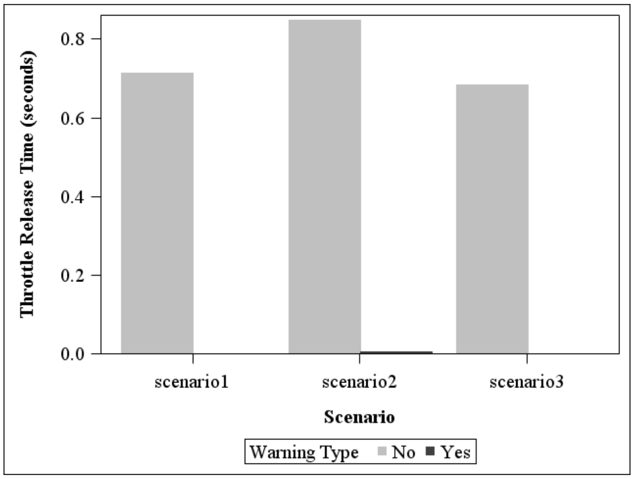
** significant at 0.05 level

* significant at 0.10 level

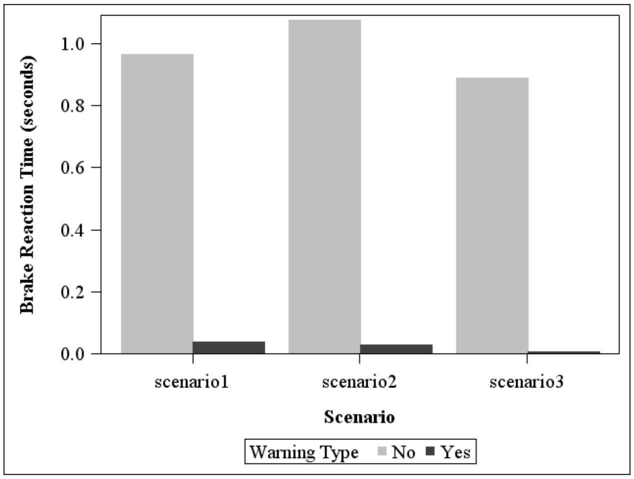
3.2.2 Response Behavior with P2V Warning

3.2.2.1 Brake Reaction Time

Figure 3.7 shows that after providing the P2V warning, the throttle release time and brake reaction time decreased significantly in all three scenarios (P-value<0.0001). In the three scenarios, throttle release time was reduced to almost 0 s. For brake reaction time in Scenario 1, the P2V warning reduced the brake reaction time from 0.96 s to 0.04 s. In Scenario 2, the warning reduced the brake reaction time from 1.07 s to 0.03 s. In Scenario 3, the warning reduced the brake reaction time from 0.89 s to 0.01 s. This indicates that the P2V warning enabled a driver to prepare for a crossing pedestrian in advance by putting the foot on the brake. After the warning, the percentages of drivers who prepared for the pedestrian crossing were 92.11%, 94.59%, and 97.44% in Scenarios 1, 2, and 3, respectively. Before the warning, the percentages were 0%, 0%, and 3.13%, respectively.



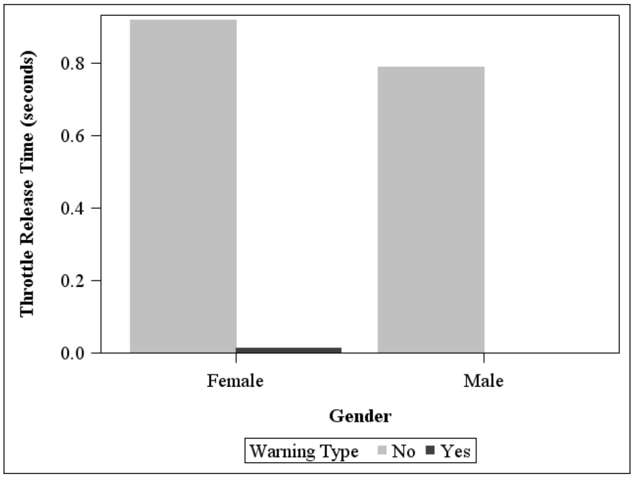
(a) Throttle release time in different scenarios



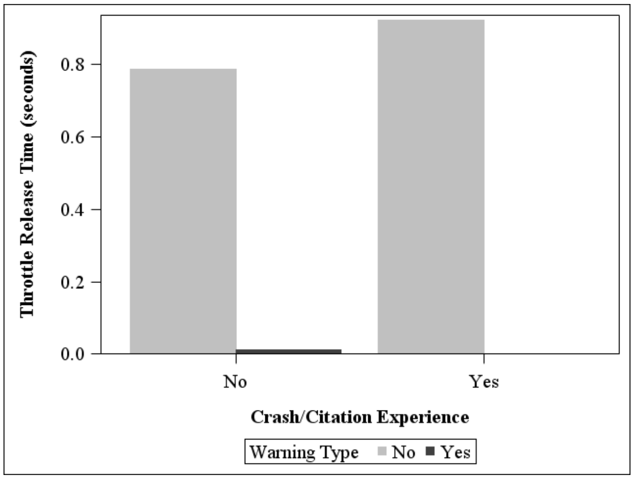
(b) Brake reaction time in different scenarios

Figure 3.7 Response process: throttle release time and brake reaction time after pedestrian appearance

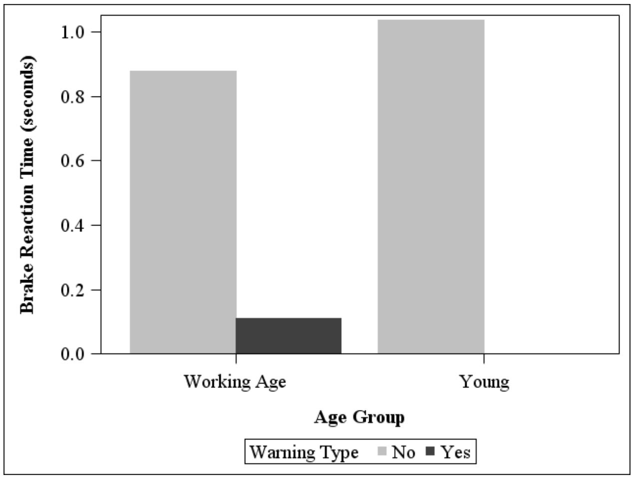
Table 3.4 shows the interaction effects of P2V warning on throttle release time and brake reaction time. For throttle release time, gender and crash/citation experience was found to interact with the warning in Scenario 2. In other scenarios, no interaction effect of P2V warning was found. In Scenario 2, the warning reduced the throttle release time from 0.79 s to 0 s for males and from 0.92 s to 0.01 s for females (Figure 3.8(a)). In Scenario 2, the warning reduced the throttle release time from 0.92 s to 0 s for drivers who had crash/citation experience in past five years compared to a reduction from 0.79 s to 0.01 s for drivers who did not have prior crash/citation experience (Figure 3.8(b)). In Scenario 1, the P2V warning effect on brake reaction time interacted with the age (P-value=0.0048). Figure 3.8(c) shows that the P2V warning reduced the brake reaction time from 0.88 s to 0.11 s for working-aged drivers and from 1.04 s to 0 s for young drivers because all drivers held the brake and prepared for pedestrian crossing. Table 1 also shows that the warning interacted with the crash/citation experience in Scenario 2 (P-value=0.039). For drivers who didn’t have crash/citation experience in the past five years, the brake reaction time to pedestrian crossing was reduced from 1.03 s to 0.06 s, while the brake reaction time to pedestrian crossing was reduced from 1.13 s to 0 s for drivers who did have crash/citation experience in the past five years (Figure 3.8(d)). The P2V warning was more effective for drivers who had crash/citation experience in the past five years.



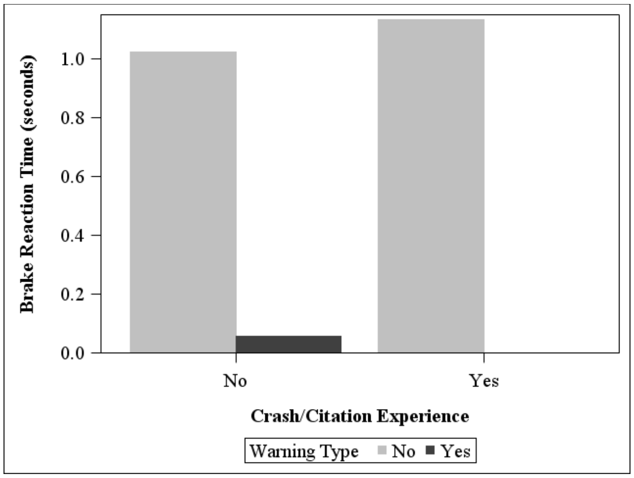
(a) Scenario 2 - throttle release time and gender



(b) Scenario 2 - throttle release time and crash/citation experience



(c) Scenario 1 - brake reaction time and age group



(d) Scenario 2 - brake reaction time and crash/citation experience

Figure 3.8 Interaction effect related to P2V warning in terms of throttle release time and brake reaction time

3.2.2.2 Brake Transition Time

Figure 3.9 shows the change of brake transition time by the P2V warning. The P2V caused little change in brake transition time in Scenario 1 (P-value=0.687) and Scenario 3 (P-value=0.755), while it significantly increased the brake transition time from 0.293 s to 0.536 s in Scenario 2 (P-value=0.013).

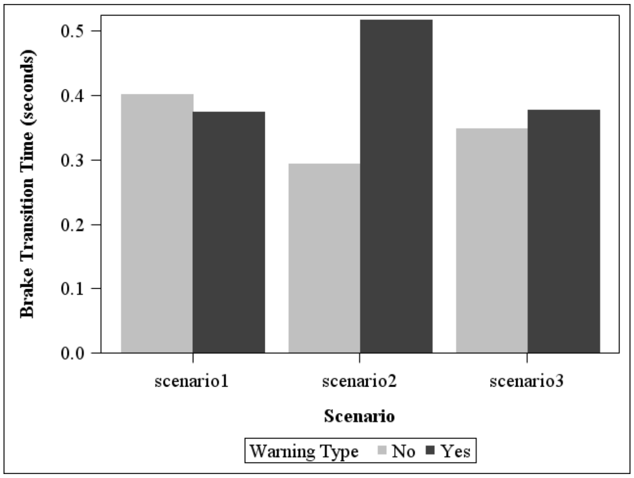


Figure 3.9 Response process: brake transition time

Table 3.4 shows that the only interaction effect with the P2V warning on brake transition time was from the crash/citation experience in Scenario 1 (P-value=0.022). Figure 3.10 shows that the P2V warning significantly reduced the brake transition time for drivers having crash/citation experience in the past five years (P-value=0.044). However, the change for drivers who did not have crash/citation experience in the past five years was not significant (P-value=0.213). No interaction effect of P2V warning with other variables was found in Scenario 2 and Scenario 3.

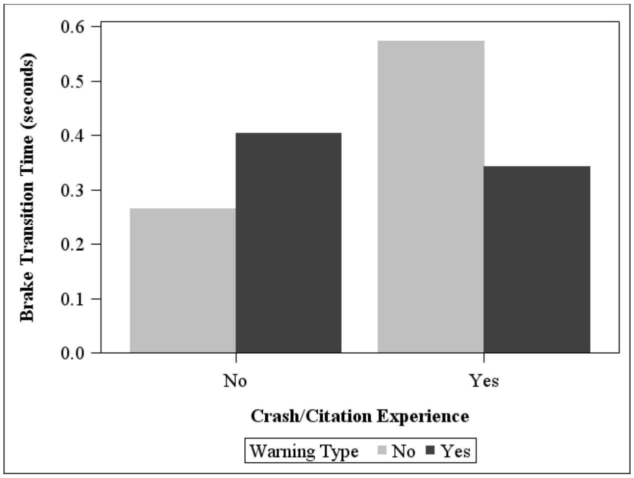


Figure 3.10 Scenario1 - Brake transition time and crash/citation experience

Table 3.4 P-value for interaction terms of P2V warning effects on response behavior

Throttle release time					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.304	0.184	0.923	0.133	0.576
2	0.847	**0.096***	**0.042****	0.225	0.421
3	0.301	0.446	0.780	0.983	0.261
Brake reaction time					
Scenario	interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	**0.005****	0.514	0.577	0.113	0.235
2	0.437	0.692	**0.039****	0.178	0.641
3	0.814	0.577	0.467	0.143	0.318
Brake transition time					
Scenario	interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.110	0.590	**0.022****	0.365	0.429
2	0.127	0.590	0.179	0.923	0.422
3	0.931	0.559	0.257	0.133	0.433

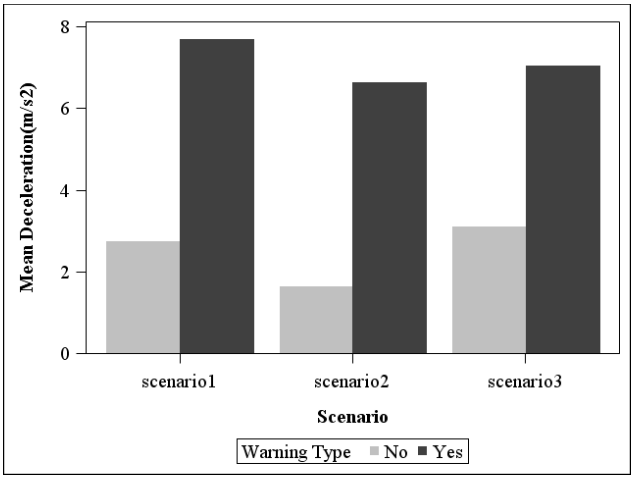
** significant at 0.05 significant level

* significant at 0.10 significant level

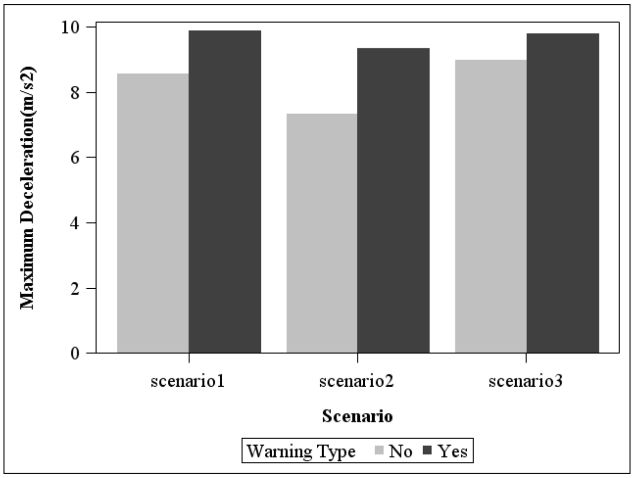
3.2.2.3 Braking Profile

Figure 3.11(a) shows that the P2V warning increased the mean decelerations in all three scenarios. In Scenario 1, the mean deceleration was increased from 2.73 to 7.73 m/s2. In Scenario 2, the mean deceleration was increased from 1.63 to 6.66 m/s2. In

Scenario 3, the mean deceleration was increased from 3.10 to 7.04 m/s2. The change of mean deceleration by warning was significant (P-value<0.0001). Figure 3.11(b) shows that, compared with mean deceleration, the change of maximum deceleration was not very significant: in Scenario 1, the maximum deceleration increased from 8.57 to 9.90 m/s2; in Scenario 2, the maximum deceleration increased from 7.32 to 9.35 m/s2; in Scenario 3, the maximum deceleration increased from 8.97 to 9.79 m/s2. The change of maximum deceleration was statistically significant in Scenario 1 (P-value=0.0028) and Scenario 2 (P-value<0.0001), but it was not statistically significant in Scenario 3 (P-value=0.1374).



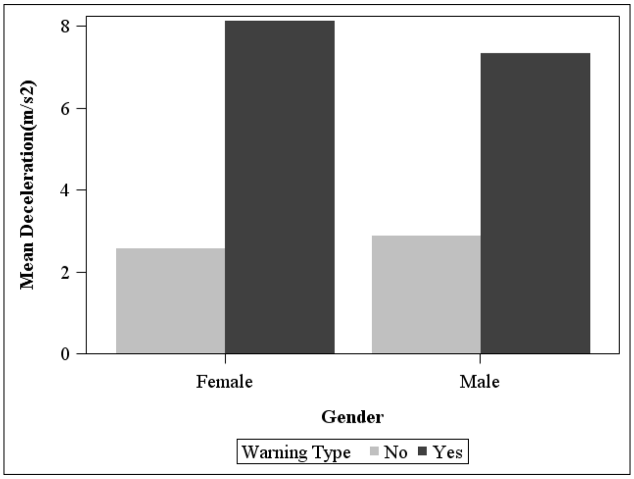
(a) Mean deceleration in different scenarios



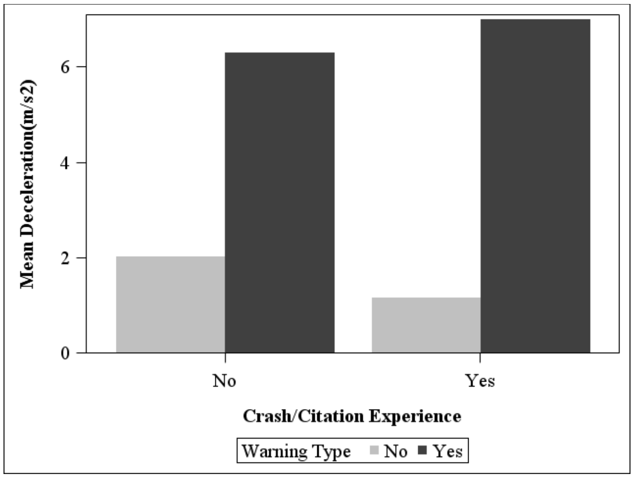
(b) Maximum deceleration in different scenarios

Figure 3.11 The change of braking profile by warning

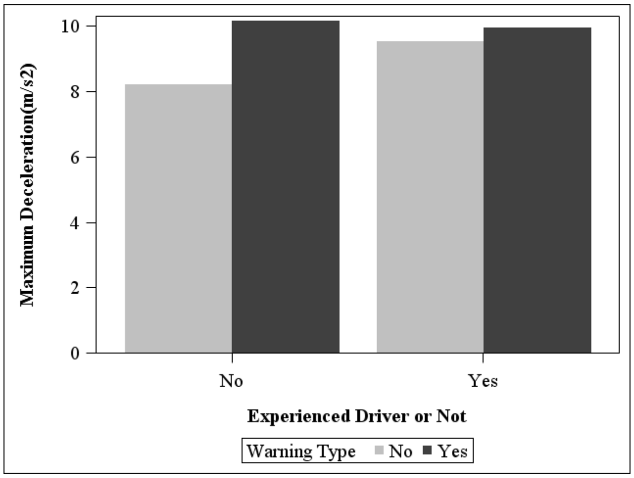
Table 3.5 shows the interaction effects of P2V warning on brake profile between scenarios. For mean deceleration, it interacted with the gender (P-value=0.087) in Scenario 1, while in Scenario 2 it interacted with the crash/citation experience (P=0.054). Figure 3.12(a) shows that in Scenario 1 the P2V warning increased mean deceleration more for female participants than male. Figure 3.12 (b) shows that in Scenario 2, the P2V warning increased mean deceleration more for drivers who had crash/citation experience in the past five years than those who did not have crash/citation experience in the past five years. For maximum deceleration, it interacted with driving experience (P-value=0.029) in Scenario 1, while in Scenario 2 it interacted with gender (P-value=0.097) and crash/citation experience (P-value=0.087). Figure 3.12(c) shows that in Scenario 1, the P2V warning only increased the maximum deceleration significantly for non-experienced drivers (P-value<0.0001) and didn't change the maximum deceleration much for experienced drivers (P-value=0.399). Figure 3.12(d) shows that in Scenario 2, the P2V warning increased the maximum deceleration for both females and males, the change for females being larger. Figure 3.12(e) shows that, in Scenario 2, the P2V warning increased the maximum deceleration for both drivers who had crash/citation experience in the past five years and drivers who did not. The change for drivers who had crash/citation experience in the past five years was larger than for those who didn't.



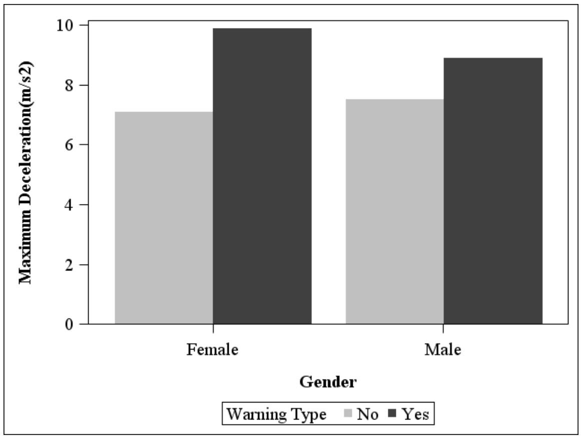
(a) Scenario 1 - mean deceleration and gender



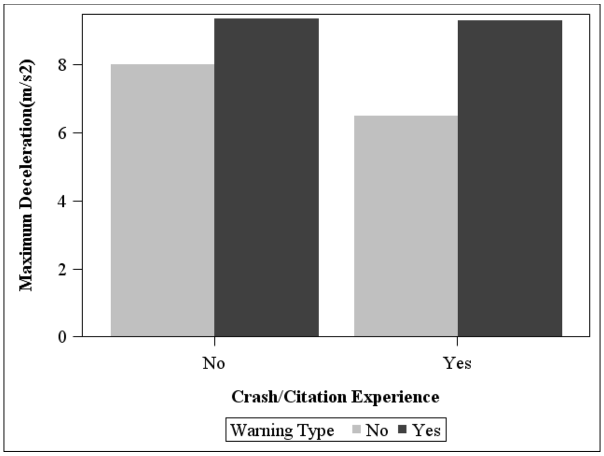
(b) Scenario 2 - mean deceleration and crash/citation experience



(c) Scenario 1 - maximum deceleration and driving experience



(d) Scenario 2 - maximum deceleration and gender



(e) Scenario 2 - maximum deceleration and crash/citation experience

Figure 3.12 Interaction effect of P2V warning on brake profile in each scenario

Table 3.5 P-value for interaction terms of P2V warning effects on braking profile

Mean deceleration					
Scenario	Interaction effect: warning*driver features				
	age	gender	crash/citation experience	education level	driving experience
1	0.141	**0.087***	0.253	0.204	0.853
2	0.675	0.896	**0.054***	0.178	0.934
3	0.470	0.843	0.845	0.715	0.611
Maximum deceleration					
Scenario	Interaction effect: warning*driver features				

	age	gender	crash/citation experience	Education level	driving experience
1	0.171	0.463	0.895	0.168	**0.029****
2	0.506	**0.097***	**0.087***	0.162	0.902
3	0.638	0.771	0.938	0.445	0.636

** significant at 0.05 significant level

* significant at 0.10 significant level

4 Discussion

4.1 FCW Warning Effect for Rear-End Pre-Crash Scenarios

4.1.1 Response Behavior Between Scenarios

The FCW warning mainly reduced the brake reaction time rather than inducing a harder brake, i.e., a smaller brake time, to achieve the safety benefits. In Scenarios 1, 2, and 3, the brake reaction time was reduced by 17.7%, 23.1%, and 19.7%, respectively. Between Scenarios 1 and 3, the throttle release time was reduced, but it was not reduced in Scenario 2. The FCW warning's effect on response behavior was also affected by driver features, and this interaction varied between scenarios. Scenario 1 differed from other scenarios. In Scenario 1, the warning type interacted with age, driving experience, and crash/citation experience; no such type of complicated interplay was found in other scenarios. In Scenario 1, the warning was much more effective for young drivers and non-experienced drivers in reducing the brake reaction time. The warning also particularly reduced the brake time for drivers who had no crash/citation experience in the past five years. Scenario 1 has fewer clues/hints for sudden braking or impending collisions than Scenarios 2 and 3. ; this may let a less-experienced driver be less careful in the scenario, which spotlights the effectiveness of FCW warning.

4.1.2 Safety Benefits between Scenarios

Figure 4.1 shows that the FCW warning had safety benefits represented by a reduction of collision rate and an increase of MMTTC in Scenarios 1, 2, and 3. Further, Table 4.1 shows that there was no interaction effect between warning types and scenarios, indicating that the trends of changing collision rate or MMTTC were similar between the three scenarios. Given that the three tracks were different in nature—Scenarios 1 and 2 were on the road segment with different speed limits, while Scenario

3 involved an intersection with a visible yellow light—the results demonstrate that the FCW warning had relatively stable effectiveness in different rear-end scenarios. However, Scenario 4 differed from Scenarios 1, 2, and 3 in that the warning did not provide significant safety benefits. In Scenario 4, the front vehicle released the turning signal before slowing down, which may have allowed the following driver enough time to notice the impending speed reduction and obtain the necessary alert. Consequently, a driver in Scenario 4 tended to brake in time even without a warning. Moreover, Table 4.1 reflects that the driver's response behavior was not significantly improved by the warning; therefore, the warning benefits were not obvious.

Table 4.1 Interaction effect of warning and track scenario

P-value	MMTTC	Collision rate
comparison group	warning type*track	warning type*track
track 1 vs 2	0.641	0.800
track 1 vs 3	0.718	0.797
track 1 vs 4	**0.096**	**0.007**
track 2 vs 3	0.891	0.766
track 2 vs 4	**0.080**	**0.007**
track 3 vs 4	**0.025**	**0.010**

Tracks affected the safety benefits of the FCW warning if considering the interaction terms. In Scenario 1, the warning was more beneficial for non-experienced drivers and young drivers: it significantly reduced 66.7% of collisions for non-experienced drivers and 67.2% for young drivers. In addition, the warning significantly increased the safety margin for non-experienced drivers so that a 176.7% increase of MMTTC was observed. However, no such interaction effects were found in Scenario 2 despite it being similar to Scenario 1 in all aspects other than a reduced speed limit. Because young and non-experienced drivers are expected to have lower driving skills in handling critical situations and higher traveling speeds, the FCW warning would be particularly useful for them. In Scenario 3, the warning mainly affected drivers who had no crash/citation experience: for these drivers, the warning reduced 75.8% of collisions and increased 163% of MMTTC. An interesting finding is that the warning did not affect these drivers in other scenarios. In Scenario 3, which simulated a dilemma situation that may cause the driver wonder whether the yellow light would turn red, a driver who had no crash/citation experience may tend to be more cautious and may be prepared for a warning.

4.2 P2V Warning for Pedestrian Pre-crash Scenarios

4.2.1 Heterogeneity between Scenarios

The three tested scenarios, as defined in Table 4.2, differed in nature. The pedestrian in Scenario 1 was hidden behind an obstruction before darting into the road. In Scenario 2, the pedestrian was always visible (walking along the road). Although the pedestrian appeared from behind an obstruction, the pedestrian was walking in Scenario 1 and running in Scenario 3. These heterogeneities of speed, position, visibility, and trajectory may result in a different information-receiving process by a driver. A driver's behavior is likely to be different as a response to the heterogeneity between scenarios. Figure 4.1 illustrates an example of a driver's different behaviors between scenarios; it plots the average velocity of participants 2 s before the pedestrian crossed the road. In Figure 4.1, the green line shows that in Scenario 3, when a participant was driving in the rightmost lane of the road approaching a parked car, they began to slow their vehicle, even though the pedestrian was still obstructed by the car from the participant. This behavior might be because the participant's driving experience enables them to be alert for a pedestrian suddenly darting into the roadway. The orange line shows that in Scenario 2, a driver sped up to pass by the pedestrian. In this situation, a driver may be concerned about whether the pedestrian walking along the road would suddenly dart out, and consequently they accelerated and tried to pass the pedestrian quickly. Facing such heterogeneity between scenarios, the P2V warning may have different effects on driver response behavior and ultimate safety benefits.

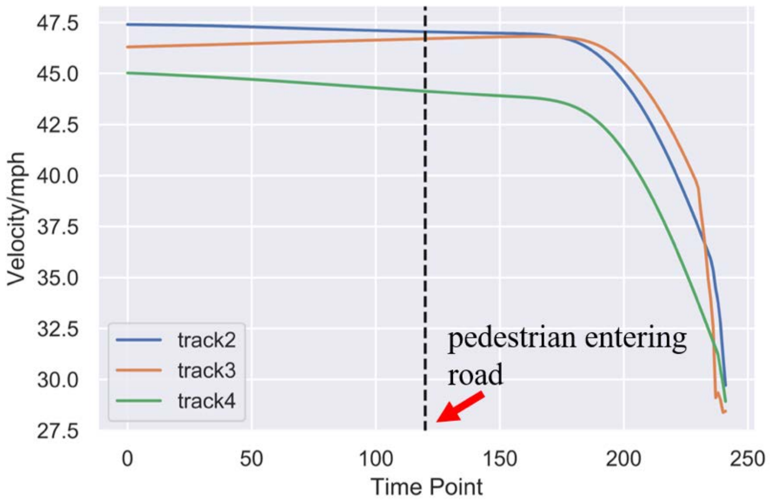


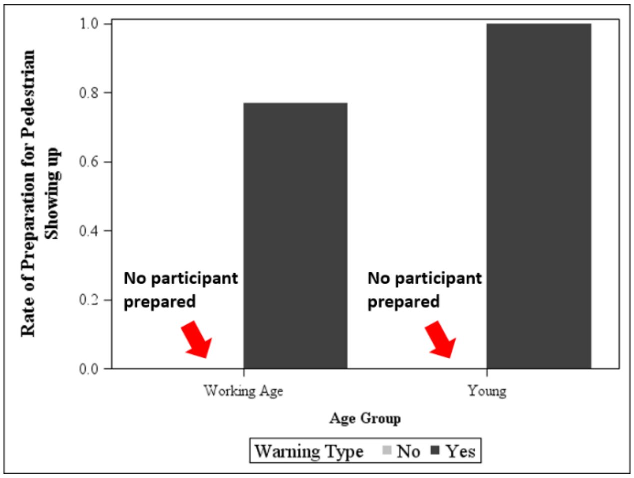
Figure 4.1 The average velocity of participants when approach the pedestrian under none-warning condition (Every 60 points represent 1 s)

4.2.2 Response Behavior between Scenarios

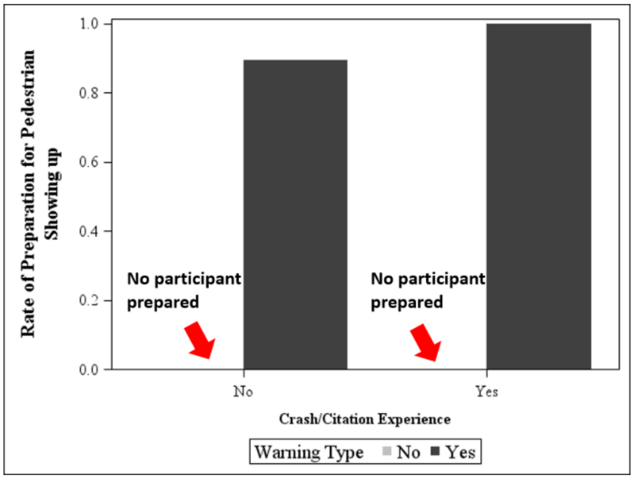
4.2.2.1 <u>Brake Reaction Time</u>

The P2V warning affected brake reaction time differently between scenarios. During the no-warning condition, the brake reaction time to the pedestrian in Scenario 2 was found to be significantly larger than that in Scenario 1 (P-value=0.014) and Scenario 3 (P-value=0.001). This indicates that a “failure to predict a visible pedestrian’s movement variation (Scenario 2)” impacts a driver more than a “failure to observe a hidden pedestrian (Scenario 2 and Scenario 3).” Compared with Scenarios 1 and 3, Scenario 2 advocated an extra paradoxical tension to the driver: the driver originally thought the pedestrian did not intend to cross, but the pedestrian did turn into the road. Consequently, the driver spent more time attempting to confirm the pedestrian movement, delaying the brake reaction. Once providing the warning, the driver obtained extra evidence that relieved this inner uncertainty, and they could respond more quickly to the pedestrian crossing. In Scenario 2, the warning significantly reduced the brake reaction time by 1.04 s (P-value<0.0001), and this reduction was also significantly larger than in Scenario 1 (0.92 s; comparison has P-value=0.034) and Scenario 3 (0.88 s; comparison has P-value=0.004). The results demonstrate that the P2V warning reduced brake reaction time more effectively in Scenario 2 than in Scenarios 1 and 3.

The P2V warning's effect on brake reaction time interacted with different factors during different scenarios. In Scenario 1, the P2V warning reduced brake reaction time for young drivers more (by 1.04 s) than working-aged drivers (by 0.77 s). This may be because young drivers are more likely to comply with the warning message. Figure 4.2(a) shows that after a warning, the percentage of young drivers preparing for a stop was 23.08% higher than working-aged drivers. In Scenario 2 after a warning, the drivers who had crash/citation experience in the past five years had greater reduction of brake reaction time (by 1.13 s) than those did not have crash/citation experience in the past five years (by 0.97 s). Figure 4.2(b) shows a reason similar to that in Scenario 1: that the drivers who had crash/citation experience adhered to the warning more than those who did not have crash/citation experience (10.53% higher).



(a) Scenario 1



(b) Scenario 2

Figure 4.2 Rate at which driver adhered to warning and prepared for the pedestrian by putting the foot on brake

4.2.2.2 Brake Transition Time

Between scenarios, the effect of P2V warning on brake transition time was different. The warning significantly increased the brake transition time in Scenario 2 by 0.24 s (P-value=0.013). This indicates that the warning enabled the participant to have a softer brake, improving driving comfort. In Scenarios 1 and 3, the warning did not change the brake transition time significantly (P-value>0.1). Additionally, although the warning didn’t have a main effect in Scenario 1, it did interact with the crash/citation experience and posted an effect on brake transition time. The results show that in Scenario 1, the warning reduced the brake transition time of drivers who had crash/citation experience in past five years, which indicates the driver braked harder under the warning condition.

4.2.2.3 Total brake operation time

Since the change in brake reaction time and brake transition time was not always in the same direction, the brake operation time (BOT), defined as the sum of the brake reaction time and brake transition time, is used to analyze the holistic effect of the two variables. The BOT measures the time from when the pedestrian began to cross the road (came into the driver's view) to when the driver reached the maximum brake. The smaller the BOT, the larger the safety margin. Figure 4.3 illustrated the change of BOT by warning in the three scenarios. After the warning, the BOT was significantly reduced in all three scenarios (P-value<0.01). A post-hoc analysis shows that this reduction was similar between scenarios (P-value>0.1). This indicates that the ultimate effect of the P2V warning on holistic brake operation was similar between scenarios. Nevertheless, the P2V warning re-allocated the time spent on the reaction to pedestrian crossing and the brake transition from a "slow reaction-hard brake" to a "quick reaction-soft brake" and resulted in a more comfortable evasive action in impending conflicts. This conversion of evasive action is particularly observed in Scenario 2 for all drivers and in Scenario 1 for drivers who had crash/citation experience in past five years.

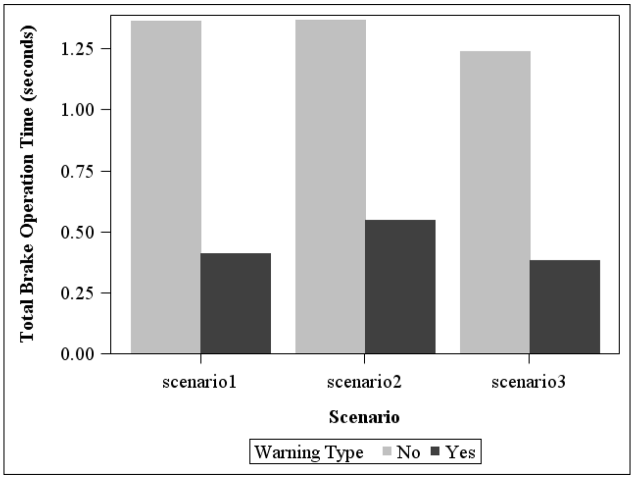


Figure 4.3 The change of total brake operation time by P2V warning

4.2.2.4 Braking Profile

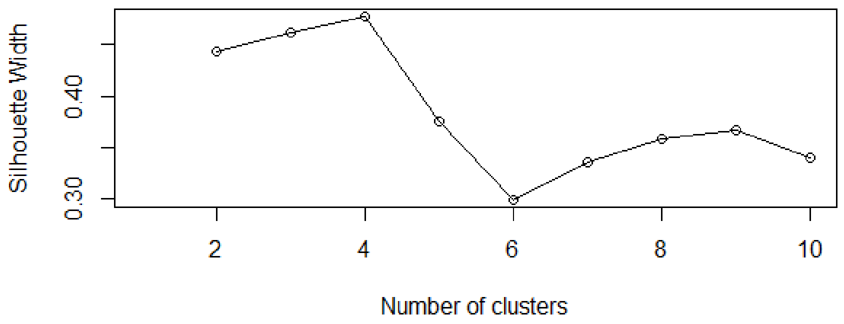
The P2V warning affected braking profile differently between scenarios. The P2V warning increased mean deceleration by 5 m/s2 in Scenario 1, by 5.03 m/s2 in Scenario 2, and by 3.94 m/s2 in Scenario 3. The increase of mean deceleration in Scenario 3 was significantly lower than that in Scenario 1 (P-value=0.069) and Scenario 2 (P-value=0.081) while the increase of mean deceleration was similar between Scenario 1 and Scenario 2 (P-value=0.949). For maximum deceleration, the P2V warning significantly increased the maximum deceleration in Scenario 1 and Scenario 2 by 1.33 m/s2 (P-value=0.0038) and 2.03 m/s2 (P-value<0.0001), respectively. The change was similar between Scenario 1 and Scenario 2 (P-value=0.238), but the warning did not have a significant effect on the maximum deceleration in Scenario 3. Since an increase in braking profile is likely to reduce the collision probability and collision/conflict severity, the P2V warning caused a positive effect on the braking profile in all three scenarios. The positive effect was less in Scenario 3 than in Scenarios 1 and 2.

The P2V warning's effect on braking profile was affected by different factors in the scenarios. In Scenario 1, the P2V warning reduced mean deceleration more for female drivers than for males. The P2V warning in Scenario 1 was effective for non-experienced drivers in reducing the maximum deceleration but not for experienced drivers. In Scenario 2, the P2V warning reduced both mean deceleration and maximum deceleration more for drivers who had crash/citation experience in the past five years than for those who did not, and it reduced maximum deceleration more for females than for males. The results also indicate that the P2V warning may be particularly useful for drivers who are less skillful, such as female drivers, non-experienced drivers, and drivers who had crash/citation experience.

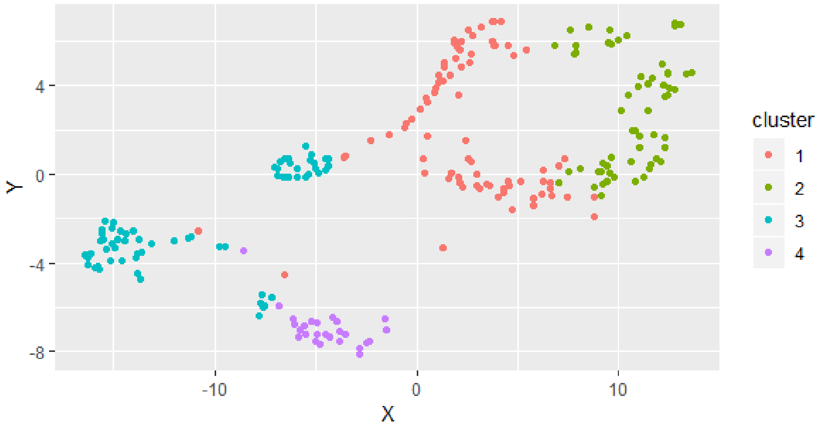
4.2.2.5 Response Strategy

The brake operation time and brake profile were combined to provide a holistic view of a driver's response strategy toward imminent collision. The response strategy can have multiple patterns of different levels of both brake operation time and brake profile, and these patterns were identified by conducting a cluster analysis.

Specifically, each response strategy pattern was represented by a cluster with a specific level of mean acceleration, maximum acceleration, brake reaction time, and brake transition time; these four variables were selected since they mostly determined the ultimate safety benefits of P2V warning. To assign each observation to a specific cluster, the silhouette width was first calculated to measure the similarity of an observation to its own cluster, compared to its nearest neighboring cluster. This step was used to find the optimal number of clusters; from Figure 4.4(a), the number of four clusters was selected because it had the highest silhouette width. Following the silhouette width, the partitioning around medoids (PAM) was used to classify the observations into four clusters. The PAM algorithm was used because it is more robust to noise and outliers than other cluster algorithms such as K-means clustering. Figure 4.4(b) shows the clustering results from a two-dimensional space. Table 4.2 shows the collision rate, the PET, and the features of brake operation and brake profile in each cluster.



(a)



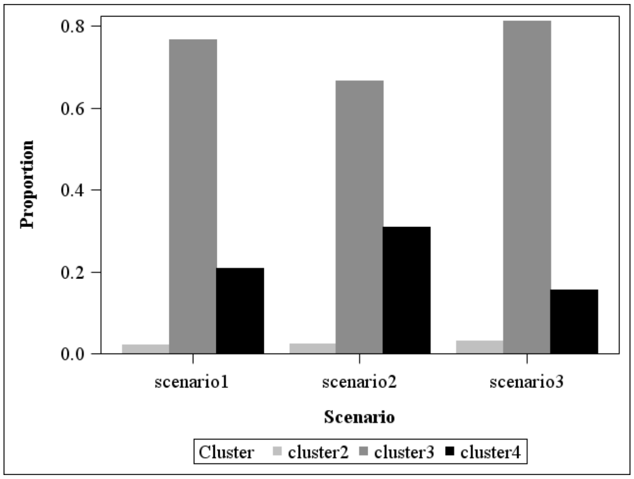
(b)

Figure 4.4 The cluster analysis of patterns of response strategy in terms of brake operation time and brake profile

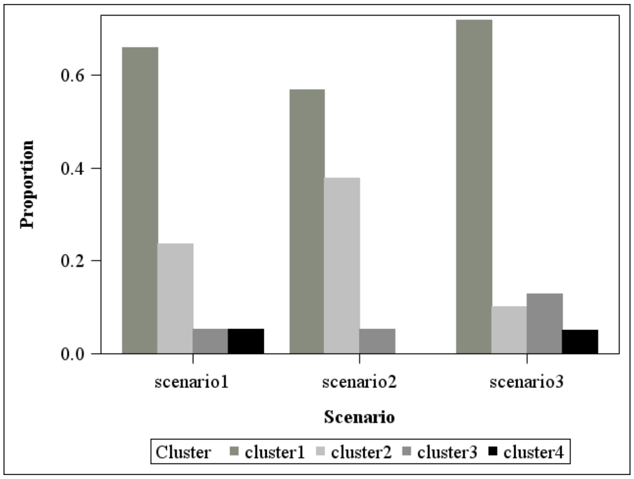
Table 4.2 Clusters and their corresponding levels of both brake operation and brake profile features.

Variable	clusters with high collision-avoidance rate		clusters with low collision-avoidance rate	
	very quick reaction + very quick & very hard brake (cluster1)	very quick reaction + very slow & hard brake (cluster2)	slow reaction + moderate slow & moderate brake (cluster 3)	very slow reaction + slow & gentle brake (cluster 4)
collision rate (%)	1.35	20.00	83.87	85.42
PET(s)	5.13	3.69	1.07	0.97
throttle release time(s)	0.00	0.04	0.62	0.86
brake reaction time(s)	0.01	0.05	0.85	1.09
brake transition time(s)	0.18	1.85	0.26	0.49
mean deceleration (m/s2)	8.30	5.38	3.05	1.13
maximum deceleration (m/s2)	10.20	9.05	9.46	4.66

From Cluster 1 to Cluster 4, the collision rate increased from 1.35% to 85.42%, and the PET decreased from 5.13 s to 0.97 s. This indicates that the corresponding response strategy became less effective in avoiding collision. The lowest collision rate and highest PET were in Cluster 1. In Cluster 1, a driver released the throttle before the pedestrian moved and only spent 0.01 s initiating the brake; the driver then pressed the brake very quickly (0.18 s) and very heavily (8.30 m/s2 for mean deceleration and 10.2 m/s2 for maximum deceleration); the response strategy pattern in Cluster 1 was labeled as “very quick reaction + very quick & very hard brake.” In contrast, Cluster 4 had the highest and lowest collision rates. In Cluster 4, a driver initiated the brake very late (1.09 s), followed by a slow depression of the brake (0.49 s) and a low level of deceleration (1.13 m/s2 for mean deceleration and 4.66 m/s2 for maximum deceleration); therefore, the response strategy pattern in Cluster 4 was labeled as “very slow reaction + slow & gentle brake.” Similarly, the response strategy patterns in Clusters 2 and 3 were defined as in Clusters 1 and 4. Interestingly, in Cluster 3, the driver had a large brake transition time (1.85 s). Since the driver had a rapid throttle-to-brake movement (represented by the small brake reaction time), this may compensate for the risky level to allow the driver a slower depression of the brake. Although the brake transition time was larger in Cluster 3, the deceleration level was still at a high level, avoiding most collisions (70%).



(a) without P2V warning



(b) with P2V warning

Figure 4.5 The proportions of response patterns (clusters) in each scenario

Figure 4.5 shows the proportions of response strategy patterns in each scenario. When there was no warning, participants rarely expected the pedestrian crossing at a distance near the participant's car, and they took more time initiating the brake. Meanwhile, participants did not have enough time to release a fast and deep depression of the brake. Therefore, Clusters 3 and 4 were prevalent in three scenarios. By providing the P2V warning, more drivers were able to select response patterns of Clusters 1 and 2, and the safety level increased. It is worth mentioning that the proportions of response patterns by warning were significantly different between scenarios (P-value=0.072); the proportions of Clusters 3 and 4 were larger in Scenario 3 than in the other two scenarios; in Scenario 2, Cluster 4 was diminished, while it still took up around 5% in Scenario 1.

4.2.3 Safety Benefits between Scenarios

The P2V warning achieved its safety benefits, namely reducing collision rate and conflict severity, mainly by reducing a driver's brake operation time and increasing the braking profile. Since the change in brake operation time and braking profile varied between scenarios, the factors contributed to safety benefits of P2V warning were different. Due to different interaction effects of the P2V warning between scenarios, the P2V warning was most effective in certain driver populations, specific to the scenario.

The P2V warning reduced collision rate significantly in all three scenarios. This was mainly because the P2V warning reduced the total brake operation time and increased the deceleration level. Due to the P2V warning, a driver can both respond to the impending conflict faster and decelerate the vehicle faster. Finally, most collisions were avoided in the given scenarios. This indicates that the P2V warning provided a stable performance regardless of the heterogeneities between scenarios. The P2V warning had an interaction effect with age in Scenario 1: specifically, the warning reduced more crashes for drivers who had crash/citation experience in the past five years than for those who didn’t. Interestingly, when there was no warning, these two groups of drivers had a similar collision rate (P-value=0.38). This indicates that the P2V warning was more effective for drivers who had crash/citation experience in the past five years in Scenario 1. The warning had varying performance because the warning decreased the brake transition time more for drivers who had crash/citation experience (P-value=0.021) than for those who didn’t (P-value=0.627). However, this interaction effect was only observed in Scenario 1. Scenarios 2 and 3 showed the heterogeneities between scenarios.

Like collision rate, conflict severity was also reduced by the P2V warning. The change in conflict severity was affected by scenarios. In this study, the conflict severity was measured by PET. The larger the PET, the smaller the conflict severity. The result shows that the P2V warning was less effective in Scenario 3. In Scenario 3, the P2V warning increased the PET by 2.73 s. In Scenarios 1 and 2, the PET increased by 3.94 s and 4.34 s, respectively. The reduction of PET in Scenario 3 by warning was significantly lower than in Scenario 1 (P-value=0.0094) and Scenario 2 (P-value=0.0002). The main reason for a less effective P2V warning in Scenario 3 was a smaller increase of braking profile than in Scenarios 1 and 2. Based on previous analysis, the P2V warning achieved a similar reduction of brake operation time between scenarios; however, the warning increased the mean and maximum deceleration much less in Scenario 3 than in Scenarios 1 and 2. Consequently, in Scenario 3, a participant did not stop as effectively as in Scenarios 1 and 2.

The P2V warning's effect on conflict severity was found to interact with different factors between scenarios. In Scenario 1, the warning reduced PET more for drivers who had crash/citation experience in the past five years than for those who did not. Because the brake transition time for this group of drivers was reduced more, they had a larger safety margin. In Scenarios 2 and 3, the P2V warning increased PET more for working-aged drivers than for young drivers. Although these two types of drivers had similar changes in brake reaction time, brake transition time, and braking profile by warning in Scenarios 2 and 3, the change in PET by warning was different. This was because drivers selected a different evasive strategy after the warning: for the working-aged drivers, in Scenarios 2 and 3, 75.0% and 92.3%, respectively, came to a complete stop until the pedestrian left the vehicle's lane. For young drivers in Scenarios 2 and 3, 52.4% and 75.0%, respectively, came to a complete stop, while 38.1% and 20%, respectively, slowed down to miss the crossing pedestrian without stopping. Therefore, the increase in PET by warning was larger for working-aged drivers than for young drivers. It is worth mentioning that the interaction effects of P2V warning were only statistically significant in specific scenarios; this again indicates that drivers respond differently to the warning based on specific scenarios.

5 Conclusions

This study involved two experiments in terms for FCW and P2V warnings. In total, four rear-end crash scenarios for FCW warning and three pedestrian crash scenarios for P2V warning were tested. The results show that FCW reduced rear-end crash by 56.6%-69.8% and P2V reduced pedestrian crash by 89.2%-97.2%.

In addition, the effects of FCW and P2V were affected by the nature of the crash scenarios. For FCW warning, the results showed similar safety benefits in the rear-end pre-crash scenarios on the straight road, while the safety benefits were not significant in right-turning scenarios since the scenario itself had conveyed enough evidence for a participant to prepare to stop. For P2V warning, the results showed obvious heterogeneities of safety benefits between scenarios. The warning was less effective in scenarios when a vehicle was approaching a pedestrian hidden behind a parked car. The disparity of safety benefits between scenarios was due to changes in brake operation, brake profile, and evasive strategies by warning. As for the interaction effects for both FCW and P2V warnings, they were found to interact with different driver features specifically to track scenarios. Finally, this study demonstrates that the effectiveness of FCW and P2V warnings was highly associated with the pre-crash scenarios. Therefore, an adaptive design of the technology toward specific track scenarios is necessary to achieve the maximum safety benefits.

References

1. Lee, S.E. et al. (2007). Analyses of rear-end crashes and near-crashes in the 100-car naturalistic driving study to support rear-signaling countermeasure development. DOT HS 810: 846.
2. National Highway Traffic Safety Administration (2017). Traffic safety facts research note: 2017 fatal motor vehicle crashes: overview. Washington, DC: National Highway Traffic Safety Administration.
3. Lee, J.D. et al. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors* 44(2): 314-334.
4. Wu, Y. et al. (2018). Effects of crash warning systems on rear-end crash avoidance behavior under fog conditions. *Transportation Research Part C: Emerging Technologies* 95: 481-492.
5. Abe, G., & Richardson, J. (2006). Alarm timing, trust and driver expectation for forward collision warning systems. *Applied Ergonomics* 37(5): 577-586.
6. Ho, C., Reed, N., & Spence, C. (2006). Assessing the effectiveness of “intuitive” vibrotactile warning signals in preventing front-to-rear-end collisions in a driving simulator. *Accident Analysis & Prevention* 38(5): 988-996.
7. Swanson, E. et al. (2016). Crash avoidance needs and countermeasure profiles for safety applications based on light-vehicle-to-pedestrian communications. Washington, DC: National Highway Traffic Safety Administration.
8. Prospect Project (2018). Proactive Safety for Pedestrian and Cyclists. Retrieved from http://www.prospect-project.eu/
9. Price, P. C., Jhangiani, R., & Chiang, I. C. A. (2015). Research methods in psychology. BCCampus..

10. Abe, G., & Richardson, J. (2014). The effect of alarm timing on driver behaviour: an investigation of differences in driver trust and response to alarms according to alarm timing. *Transportation Research Part F: Traffic Psychology and Behaviour* 7(4-5): 307-322.
11. Wilson, T.B. et al. (1997). Forward-looking collision warning system performance guidelines. *SAE Transactions* 106: 701-725.
12. Wu, X. et al. (2018). The effectiveness of auditory forward collision warning alerts. Transportation Research Part F: Traffic Psychology and Behaviour 59: 164-178.
13. Ozbay, K. et al. (2008). Derivation and validation of new simulation-based surrogate safety measure. *Transportation Research Record* 2083(1): 105-113.
14. Wu, J., Radwan, E., & Abou-Senna, H. (2018). Determination if VISSIM and SSAM could estimate pedestrian-vehicle conflicts at signalized intersections. *Journal of Transportation Safety & Security* 10(6): 572-585.
15. Lord, D. (1996). Analysis of pedestrian conflicts with left-turning traffic. *Transportation Research Record* 1538(1): 61-67.
16. Gower, J.C. (1971). A general coefficient of similarity and some of its properties. *Biometrics* 27(4): 857-871.
17. Rokach, L., & Maimon, O. (2005). Clustering methods. In O. Maimon & L. Rokach (Eds.) *Data Mining and Knowledge Discovery Handbook* (pp. 321-352). New York: Springer.
18. Moser, E.B. (2018). Repeated measures modeling with PROC MIXED. Retrieved from https://support.sas.com/resources/papers/proceedings/proceedings/sugi29/188-29.pdf