Investigating the Effects of Smartphone-based P2V Warning Using Driving Simulator Experiments

SAFETY RESEARCH USING SIMULATION
UNIVERSITY TRANSPORTATION CENTER

Yina Wu, PhD, PI
Research Associate Professor
Department of Civil, Environmental and Construction Engineering
University of Central Florida

Mohamed Abdel-Aty, PhD, Co-PI
Pegasus Professor, Chair
Department of Civil, Environmental and Construction Engineering
University of Central Florida

Lishengsa Yue
Postdoc Researcher
Department of Civil, Environmental and Construction Engineering
University of Central Florida

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Yina Wu, PhD, PI
Research Associate Professor
Department of Civil, Environmental and Construction Engineering
University of Central Florida
https://orcid.org/0000-0001-6516-8144

Mohamed Abdel-Aty, PhD, PE, Co-PI
Pegasus Professor, Chair
Department of Civil, Environmental and Construction Engineering
University of Central Florida
https://orcid.org/0000-0002-4838-1573

Lishengsa Yue
Postdoc Researcher
Department of Civil, Environmental and Construction Engineering
University of Central Florida
https://orcid.org/0000-0002-0864-0075

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Yina Wu, PhD, PI https://orcid.org/0000-0001-6516-8144
Mohamed Abdel-Aty, PhD, PE, Co-PI https://orcid.org/0000-0002-4838-1573
Lishengsa Yue https://orcid.org/0000-0002-0864-0075

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16. Abstract
The pedestrian-to-vehicle (P2V) technology is expected to reduce pedestrian crashes and improve roadway safety. Utilizing the smartphone as a communication platform could make the P2V more applicable for old cars without having additional retrofits. In UCF's previous work, the effectiveness of a general P2V design has been demonstrated. However, the influence of different P2V designs remains uncertain.

This research focuses on the influence of P2V designs in different scenario conditions and uncovers some insights about potential variations between drivers, for the sake of better informing drivers about potential pedestrian risk situations in the upcoming automation era.

Two aspects of P2V design, i.e., the warning display mode and warning content, were tested in six pedestrian pre-crash scenarios. The warning display mode is categorized into a gradually changed warning and an emergency warning; and the warning content is referred to whether having specific distance information as a supplement or not. Thirty- six valid participants were tested in the simulator. The results demonstrate that the gradually changed warning and considering additional information would be better in terms of safety and driving performance. In addition, the effectiveness of the P2V design can be further improved when considering the scenario and drivers' features.

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Abstract

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This research focuses on the influence of P2V designs in different scenario conditions and uncovers some insights about potential variations between drivers, for the sake of better informing drivers about potential pedestrian risk situations in the upcoming automation era.

Two aspects of P2V design, i.e., the warning display mode and warning content, were tested in six pedestrian pre-crash scenarios. The warning display mode is categorized into a gradually changed warning and an emergency warning; and the warning content is referred to whether having specific distance information as a supplement or not. Thirty- six valid participants were tested in the simulator. The results demonstrate that the gradually changed warning and considering additional information would be better in terms of safety and driving performance. In addition, the effectiveness of the P2V design can be further improved when considering the scenario and drivers' features.

1 Introduction

The pedestrian crash has caused a significant portion of total traffic fatalities in the United States; in 2018, 6227 pedestrians were killed in the traffic crashes and this takes up for 15% of the total traffic fatalities [1]. The pedestrian-to-vehicle warning (P2V) system in a connected vehicle environment is considered a promising countermeasure to reduce pedestrian crashes. Given that the era of connected vehicle technology is coming and traffic objects can easily "communicate" with each other, the P2V system has its technical feasibility. With P2V systems, a pedestrian could share his/her location information to nearby drivers within a certain range in case that the drivers failed to observe the pedestrian. Thus, drivers could be more alert of the potential upcoming events, such as pedestrian crossing.

An efficient way to fulfill the P2V system is through the widely used smartphones. The pedestrian can broadcast his/her location to the nearby receivers by using the localization sensors and communication units of the smartphone. The driver can receive such broadcasting information also by using the smartphone. This is expected to be realistic and practical since no additional cost is needed for the retrofits, particularly for older car models.

While there remain several concerns when developing such a smartphone-based P2V system. The first concern is about the adaptation ability of such a system between different scenarios. Many studies have proved that warning systems may receive different effects when the traffic complexity is changed. Starkey et al. [2] designed a smartphone-based intelligent speed assistance (ISA) App to recommend driving speed to drivers; they found that drivers followed the ISA suggestions more on high-speed limit roads while disengaged the ISA when they were driving on a low speed rural road. Várhelyi et al. [3] evaluated the performance of a driver assistance system in terms of speed compliance and distance gap maintenance to the front car; they realized that the drivers may rely on the system too much that they tend to drive more aggressively if the system does not give them warning. This might because the variation of volume and complexity of information in different scenarios results in adverse impacts on the decision-making process [4]. Yue et al. [5] analyzed the effects of Forward Collision Warning (FCW) systems in the freeway scenarios, the arterial scenario and the intersection dilemma zone scenario. They identified that the intersection dilemma zone scenario and freeway scenarios might deteriorate a driver's ability to adapt to the FCW.

The second concern is about the P2V system design. The design should increase driver knowledge, awareness & learning, and motivate drivers to perform better-driving behavior [6-8]. Currently, less is known about the effects of displaying content of the system, the displaying timing, and whether the design should be changed according to the scenario conditions. The conclusions from previous studies are quite inconsistent. Some researchers suggested providing detailed warning information to drivers such as the size of gap distance between conflicting parties and the safety of the gap; also, they proved that dynamic warning information related to the traffic condition would be better [9, 10]. However, some other researchers found that detailed or dynamic warning information may have no significant effects. In Jahn et al.'s research [11], they tested the effects of two route guidance systems of different display sizes and display organizations using the peripheral detection task performance as the metric. However, they failed to identify significant differences between the two types of designs. Similarly, Davidse et al. [12] designed an advanced driver support system that provides traffic information and early warning. They expected the system to help drivers reduce their workload; however, contrary to expectations, all support messages failed to reduce workload. In another research conducted by Vaezipour et al. [6], they found that the warning system combining advice and feedback significantly increases the driver workload.

The third concern is how different drivers would use the system. Some aggressive drivers may not follow the system recommendation when it contradicts their preference. Lai et al. [13] found that the drivers who tend to speeding were least likely to use the ISA. On the contrary, Yue et al. [14] found that the P2V system is most beneficial for drivers who had been involved in crashes or received citations in the past five years. Therefore, It might be more efficient to enable a customized system, in other words, to determine the way the advice and feedback that the system presents depending on its users [6].

The above issues reflect that the P2V system performance is highly varied depending on the interaction effects between the system, the driver and the scenario condition. The objective of this research is to investigate the effects of smartphone-based P2V systems, particularly considering the interaction effects between scenario conditions, system designs, and driver features. Since the safety benefits of P2V warning system have been demonstrated in our previous work [15], this research would focus more on the optimal design of the P2V system in different scenario conditions and uncover insights about potential variations between drivers, for the sake of better informing drivers about potential pedestrian crash risks in the upcoming connected and automated era.

2 Methodology

2.1 Apparatus

The apparatus has two components (Figure 2-1): the first one is the National Advanced Driving Simulator (NADS MiniSim), which is used to collect driver behavior data and provide virtual driving scenarios; the simulator has three screens that provide a 130-degree forward field-of-view. The second is a smartphone/iPad. This study used an iPad, which is similar to the smartphone regarding the communication function and also similar to the display platform in current luxury vehicles.

Figure 2.1 The driving simulator experiment

Conceptually, the P2V works in the following order: both the pedestrian and the driver publish their position information (through the smartphone) to the cloud, and the cloud would calculate the crash risk and determine the warning display mode. The driver's smartphone subscribes to the warning information that is displayed on the screen. In the simulator settings, a third-party script was customized by the research team to extract real-time driving and pedestrian data from the simulator and feed them to the pedestrian warning algorithm. The warning information result was then published by the Redis database (cloud) to a backend server. On the server, the warning display interface would be finally generated and subscribed by the driver's smartphone. The overall delay was acceptable and cannot be noticed by the participant. The driver would receive different designs and modes of pedestrian warning based on specific driving scenarios and dynamic location information of the driver and pedestrian. The whole process is shown in Figure 2-2.

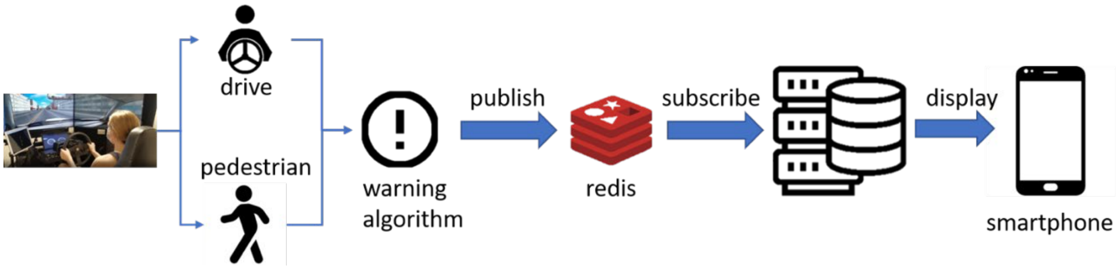


Figure 2.2 The virtual communication between a nearby pedestrian and driver

2.2 Scenario Design

According to Yue et al.'s research [16], typically, there are ten pedestrian pre-crash scenarios which can be categorized into three groups: I. vehicle going straight and pedestrian crossing/adjacent to/in the road, II. vehicle turning left and the pedestrian crossing the road, and III. vehicle turning right and the pedestrian crossing the road. The formal driving simulator experiment includes six scenarios (Table 1); Scenarios 1,2,4,5 and 6 were all from group I, and scenario 3 was from group II. These scenarios were decided based on the simulator's ability to provide an approximately realistic driving scenario. Some scenarios from group II (left-turning related) and III (right-turning related) were excluded because the visual depth, vision angle, and other restrictions prevent forming a realistic driving experience for the driver after pre-validation testing. The reason for the pedestrian crash is also listed in Table 2.1.

2.3 Warning Design

Different warning designs were adopted in each scenario. The P2V warning design tests two issues: I) warning display mode: whether a gradually changed warning (e.g., warning color changes from “white” to “yellow” and then “red” based on the situation severity) is better than an emergency warning (e.g., first activated at the timing of “red” warning icon), and II) warning content: whether some additional information can assist drivers in making decisions (e.g., lateral distance information). The detailed settings of each warning design are presented in Table 2.2.

For scenarios 1,3 and 4, the warning display mode was tested, and the warning would activate at different thresholds. Two types of activation modes were adopted: the time gap (using time-to-collision, TTC as the metric) based activation and distance gap-based activation (using the specific distance between the pedestrian and the driver). For time gap-based activation, the TTC of 3.0 s was used to represent an emergency warning with a “red” warning icon and quick beeping audio when the warning activates, while the TTC of 7.0 s represented a gradually changed warning with a “yellow” warning icon and slow beeping audio when the warning activates. Both the color of the warning icon and frequency of the beeping audio were dynamically changed according to the metric values; in other words, if the TTC becomes larger due to a brake, the warning icon color might go back from “red” to “grey” and the beeping frequency would decrease as well. It worth mentioning that a TTC of 3.0 s is relatively sufficient to achieve a timely warning [17-19]. Therefore, the major difference between the two thresholds was whether the warning information would be displayed in a gradually changed way. Similar settings were applied to the distance-based activation.

For scenarios 2, 5 and 6, the warning content mode was tested. Specifically, scenario 2 was used to confirm whether the pedestrian’s crossing intention notification would benefit a driver; scenario 5 was testing whether additional lateral distance information was useful; and scenario 6 was used to test whether basic pedestrian distance information (without beeping audio) would benefit drivers or not. Similar to other scenarios, the warning design was always dynamic; the distance indicator and the color of the warning icon would be changed according to related distance metrics.

2.4 Experimental Design

The experiment was a within-subjects experiment. Each scenario has two types of warning designs; each participant driver experienced all warning designs in all scenarios in a randomized order. 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 [20]. Many additional scenarios were also added in the experiment; these scenarios had similar configurations, such as obstruction size and traffic background with other scenarios which were designed for the testing; the only difference is that additional scenarios did not have a pedestrian as a conflict object. By providing these additional scenarios, memory effects that participants may predict an impending conflict with the pedestrian could be avoided [14]. The total length of the testing track was around 25 minutes.

2.5 Dependent and Independent Variable

The independent variable is the P2V warning design; meanwhile, the driver features are also considered for the interaction effects. In terms of driver features, only three variables were analyzed (Table 2-3); and these variables are: 1) not-at-fault crash experience: whether the driver has been involved in any crash that was not the driver's fault in last five years; 2) citation experience: whether the driver received any citation in the last five years; 3) ADAS experience: whether the driver has experience of using any advanced driving assistance system such as blind-spot warning. These variables were selected because they can achieve a statistical power of greater than 0.8 [21] in terms of capturing a middle size effect of 0.3 [22]. Other driver features were not analyzed in this study due to the imbalanced sample size.

The dependent variables (Table 2-3) were driver performance variables recorded from each process of a driver's decision making. Specifically, dependent variables were collected from the start of the critical event (the warning was released) to the end of the scenario (either of three conditions is satisfied: the driver was completely stopped, the driver hit the pedestrian (the driver failed to stop), the time point when the driver and pedestrian became minimum (the driver slowed down without stopping, but missed the pedestrian).

In addition to driving performance variables, the safety metric (i.e., the collision rate) was also analyzed for each P2V warning design.

2.6 Participants and Procedure

Institutional Review Board (IRB) approval was obtained before starting the experiments. In total, 41 participants ran the experiment and 36 were valid samples (without having motion sickness and followed experiment instructions). The participants had an average age of 25.8. Each participant held a valid driving license.

Upon arriving at the driving simulator lab, each participant completed both a consent form and a demographic survey. Then, they were instructed about the possible warning design they might meet during the experiment. Before the formal experiment, each participant was given a practice drive to get used to the simulator and the warning design. The participant was told to use the brake rather than swerving to avoid hitting the pedestrian if possible. In the real world, it is quite often that a car occupies the adjacent lane on the left side; therefore, the swerving maneuver to avoid a pedestrian is not always possible.

Table 2.1 Scenario settings

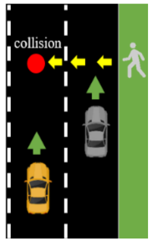
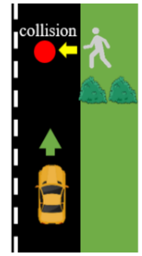
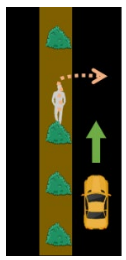
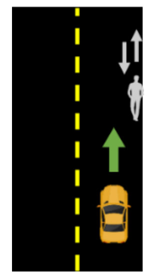
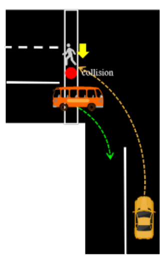
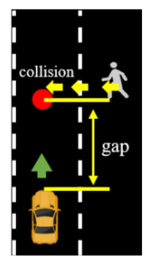
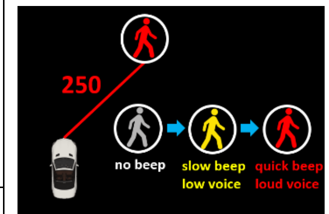
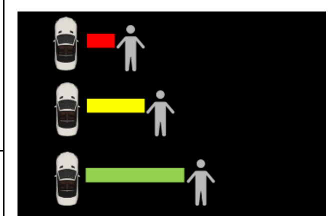
Scenario ID	Scenario Configuration	Pre-Crash Scenario Description	Scenario ID	Scenario Configuration	Pre-Crash Scenario Description
1 (short name for “walk from behind adjacent car”)		The pedestrian is hit by the yellow car since the pedestrian is obstructed by the gray car on the right lane	4 (short name for “walk from behind bush”)		The pedestrian walks into the drive lane from behind the bush. The yellow car failed to observe the pedestrian in time.
2(short name for “suddenly walk into road”)		The pedestrian is hit by the yellow car since the pedestrian suddenly changes trajectory and enters the road	5(short name for “walk along curb”)		The pedestrian is walking in the driver lane and hit by the yellow car’s side mirror because the driver failed to keep enough lateral space. The scenario 5 has two sub-scenarios: 5-1 ("walk along curb-farther") has a pedestrian keeping 1.5 feet to the road curb; while 5-2 ("walk along curb-closer") has a pedestrian keeping 3.0 feet to the road curb.
3(short name for “walk from behind right turning car”)		The pedestrian is hit by the yellow car during the left-turning movement since the pedestrian is obstructed by the gray big car which is turning right	6(short name for “observed crossing”)		The pedestrian is crossing the street and hit by the yellow car since the yellow car does not yield to the pedestrian.

Table 2.2 P2V warning design in each scenario

Scenario ID	Warning Type	Activation condition	Warning Design	Warning Content Design
1	base	TTC <= 3.0 s (emergency warning design)	When TTC < 3.0 s, displaying red warning icon, distance and quick beeping audio; when TTC is between 3.0 – 7.0 s, displaying yellow warning icon, distance and slow beeping audio; when TTC > 7.0 s, displaying white warning icon, distance and no beeping audio	 Applied to scenarios 1, 3, and 4
	test	TTC <= 7.0 s (gradually changed warning design)		
2	base	not activated	when distance < 200 feet, displaying crossing intention icon	
	test	distance < 200 feet (without the P2V system)		
3	base	distance < 120 feet (emergency warning design)	When distance is between 400-600 feet, displaying white warning icon, distance and no beeping audio; when distance is between 120-400 feet, displaying yellow warning icon and slow beeping audio; when distance < 120 feet, displaying red warning icon and quick beeping audio;	 Applied to scenario 2
	test	distance < 600 feet (gradually changed warning design)		
4	base	TTC <= 3.0 s (emergency warning design)	When TTC < 3.0 s, displaying red warning icon, distance and quick beeping audio; when TTC is between 3.0 – 7.0 s, displaying yellow warning icon, distance and slow beeping audio; when TTC > 7.0 s, displaying white warning icon, distance and no beeping audio	
	test	TTC <= 7.0 s (gradually changed warning design)		 Applied to scenario 5
5	base	not activated (without the P2V system)	when distance < 500 feet, displaying lateral distance-status icon	
	test	distance < 500 feet (providing additional information)		
6	base	not activated (without the P2V system)	When distance is between 400-600 feet, displaying white warning icon and distance; when distance is between 200-400 feet, displaying white warning icon and distance; when distance < 200 feet, displaying red warning icon and distance; there is no beeping audio in any conditions	 Applied to scenario 6
	test	distance < 600 feet (providing additional information)		

*All "distances" in this table mean the distance-to-pedestrian

Table 2.3 Variable definition

Driver performance variables			Driver features			Safety		
Variable ID	Variable name	Variable definition	Variable ID	Variable name	Variable definition	Variable ID	Variable name	Variable definition
1	throttle to release time (TRT)	The time between the warning release and the time of participant completely release the throttle	1	not-at-fault	Whether the driver has been involved in any vehicular crash which was not the driver's fault in last 5 year; Yes=1, No=0	1	collision rate	The percentage of collision event among the same scenarios across all participants
2	brake reaction time (BRT)	the time between the warning release and the time of participant begins to brake.	2	citation	Whether the driver received any citation in last 5 year; Yes=1, No=0	\	\	\
3	brake-to-maximum brake time (BTMB)	the time spent by a driver to reach their own maximum deceleration after the initial depression of the brake pedal	3	ADAS	Whether the driver has experience of using any advanced driver assistant system; Yes=1, No=0	\	\	\
4	mean deceleration	The mean deceleration during the period*	\	\	\	\	\	
5	max deceleration	The max deceleration during the period*	\	\	\	\	\	\
6	jerk	The maximum jerk (the deviation of acceleration) during the period*	\	\	\	\	\	\
7	stop indicator	Whether the driver is stopped; stop=1, non-stop=0	\	\	\	\	\	\
8	minimum distance	The minimum distance between the pedestrian and the driver during the period*	\	\	\	\	\	\
9	Stopping distance	The distance between the pedestrian and the driver if the drive stopped	\	\	\	\	\	\

* the period is from the time of the warning release to the end of the event; the end of the event is indicated by either the driver is completely stopped, the pedestrian left the conflict zone, or the driver hit the pedestrian; depends on which time point is earlier.

3 Results

This study used the within-subjects repeated measurement ANOVA analysis. The approach was conducted by the SAS correlated errors model, which has the form as shown below [23]:

$$Y_{ij} = \mu + \tau_i + \tau_i * \alpha_i + B_j + \varepsilon_{ij}$$

Where Yij is the response measured with specific warning type, 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 $(0,\sigma_B^2)$, ε ~N $(0,\sigma_\varepsilon^2)$.

3.1 Variation of P2V System Between Different Designs

3.1.1 Collision Rate

This study is an extension of our previous work [15] in which the general safety benefits of P2V warning systems has already been demonstrated. As abovementioned, the P2V warning design can be regarded as an efficient design since the warning was provided in advance with sufficient time in all scenarios; therefore, the crash rate in all scenarios was relatively low and sometimes even zero. In scenarios 3 and 6, no crash occurred. For scenario 5, under each type of P2V system design two crashes occurred, no difference was observed.

In scenario 1 ("walk from behind adjacent car"), the collision rate (the percentage of crash cases among total cases under a specific situation (P2V design & pre-crash scenario)) under the base P2V system design was 30%, which was significantly higher than the test P2V system design ($F=15.20$, $p<0.001$); similarly, in scenario 4 ("walk from behind bush"), the base P2V system design had a higher collision rate of 24%, significantly different from the test P2V system design (0%).

3.1.2 Brake Reaction Time

Figure 3.1 shows the BRTs between the base and test conditions in different scenarios. Scenario 5 (“walk along curb”) is not considered since the driver was supposed to use the steering wheel to avoid hitting the pedestrian. In scenario 1 (“walk from behind adjacent car”), the BRT in the test condition is 1.81 s on average, which was significantly larger (p-value<0.001) than that in the base condition (0.84 s); in scenario 2, the BRTs in the test and base conditions were not significantly different (p-value=0.499), which were 0.64 s and 0.76 s respectively; in scenario 3, the test condition had a significantly larger BRT of 2.34 s, compared with a BRT of 0.88 s in the base condition (p-value<0.001); similar results were found in scenario 4, that the BRT in the test condition (1.72s) was significant larger (p-value<0.001) than that in the base condition (0.68s). Contrary to scenarios 1, 3 and 4, the BRT in scenario 6 was larger in the base condition (2.34s) than that in the test condition (1.76s), with a p-value=0.012. Detailed statistical descriptions of BRT in each scenario can be found in Table 4.

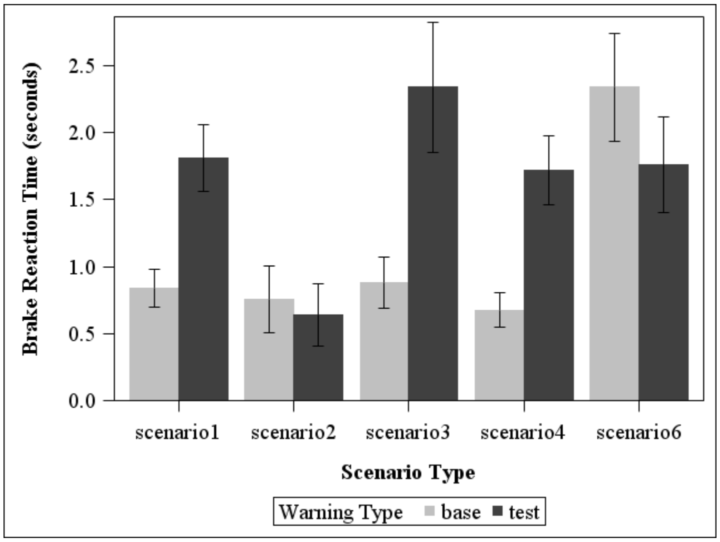


Figure 3.1 BRT between the base and test conditions in each type of scenario

3.1.3 Throttle to Release Time

Figure 3.2 shows the TRT variation between base and testing conditions in different scenarios. The TRTs were found to be significantly larger in the test condition in scenarios 1 (“walk from behind adjacent car”), 2 (“suddenly walk into road”), 3 ("walk from behind right turning car"), and 4 ("walk from behind bush"); while in scenarios 5 ("walk along curb ") and 6 ("observed crossing") the TRTs were found to be significantly larger in the base condition. Specifically, the TRTs in scenarios 1 and 4 had a significant positive difference of 0.7s and 0.75s between the test and base conditions respectively, while it had a significant negative difference of 2.47 s in scenario 5-2 ("walk along curb-closer") between two conditions.

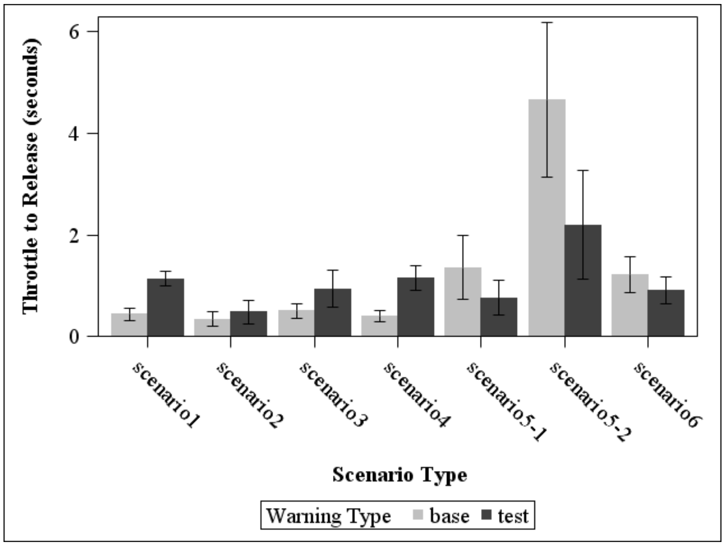


Figure 3.2 Throttle release time between the base and test conditions in each type of scenario

3.1.4 Brake-to-Maximum Brake Transition Time

In terms of the BTMB, it was detailed in Table 4 and Figure 3.3. In scenario 1 ("walk from behind adjacent car"), it was 2.24s in the test condition compared with 1.39s in the base condition, and the difference was significant (p-value=0.0031); in scenario 2 the BTMB was similar between the test and base conditions with a value close to 1.3s (p-value=0.783); in scenario 3 ("walk from behind right turning car") the BTMB was significantly larger (p-value < 0.001) in the test condition with a value of 11.00s, however, in the base condition it was only 1.32s; in scenario 4 the BTMB was similar between the test and base conditions with values of 1.65s and 1.32s respectively (p-value = 0.257); similar to scenario 4, in scenario 6 the BTMB was not significantly different from each other (p-value = 0.364). Scenario 5 is not considered since the driver was supposed to use the steering wheel to avoid hitting the pedestrian. Figure 5 shows the Brake to maximum brake time between base and test conditions in each type of scenario.

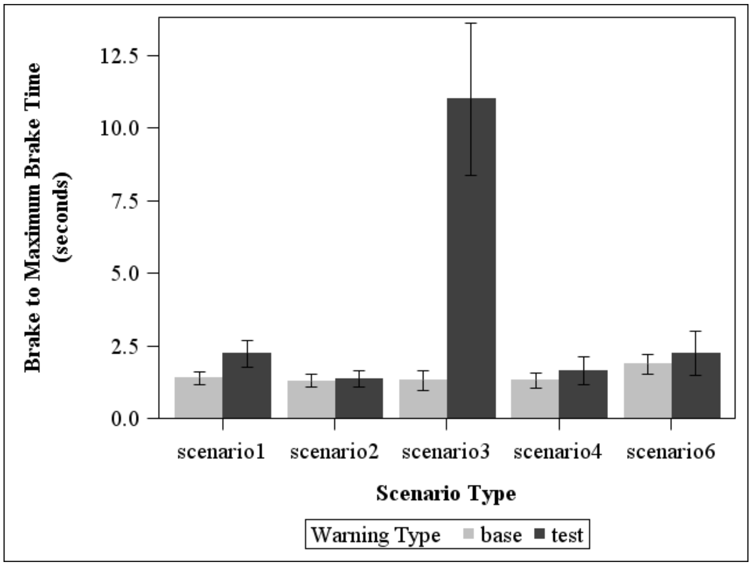


Figure 3.3 Brake to maximum brake time between the base and test conditions in each type of scenario

3.1.5 Mean Deceleration

Figure 3.4 shows the mean deceleration between base and test conditions in each scenario. The mean deceleration was found to be significantly different between the base and test conditions in scenarios 1, 3, and 4. Specifically, in scenario 1(“walk from behind adjacent car”), the mean deceleration was 1.86 m/s2 in the test condition, which was significantly lower (p-value < 0.001) than that in the base condition (5.04 m/s^2); in scenario 3 ("walk from behind right turning car"), the mean deceleration was 0.88 m/s2 in the test condition, which was significantly lower (p-value < 0.001) than that in the base condition (1.32 m/s^2); similarly, in scenario 4 ("walk from behind bush"), the mean deceleration in the test condition was 1.70 m/s^2 while it was 5.29 m/s^2 in the base condition. However, in scenarios 2, 5 and 6, the mean deceleration was similar between the two types of conditions.

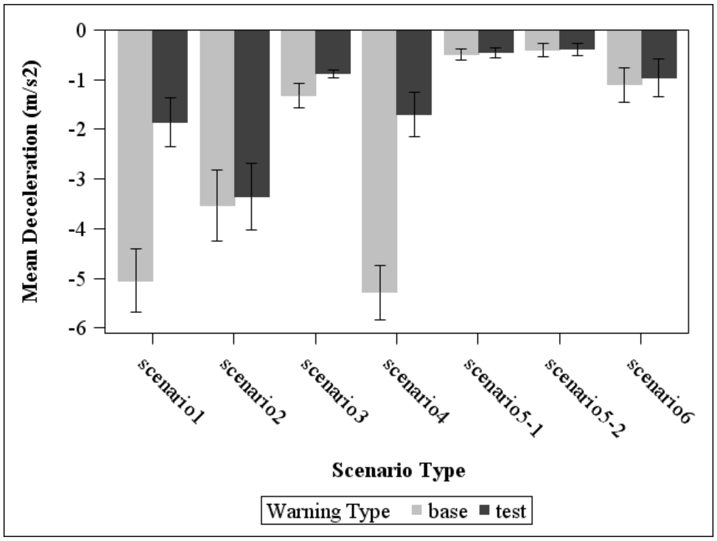


Figure 3.4 Mean deceleration between the base and test conditions in each type of scenario

3.1.6 Maximum Deceleration

As for the max deceleration, it was found significantly larger (p-value < 0.001) in scenarios 1 and 4 (base P2V design); however, no significant difference was found in other scenarios. Specifically, in scenario 1 (“walk from behind adjacent car”), the max deceleration was 6.83 m/s^2 in the test condition while it was 9.31 m/s^2 in the base condition; in scenario 4 ("walk from behind bush"), the max deceleration was 6.46 m/s^2 in the test condition while it was 9.65 m/s^2 in the base condition. Figure 3.5 shows the max deceleration between base and test conditions in each scenario.

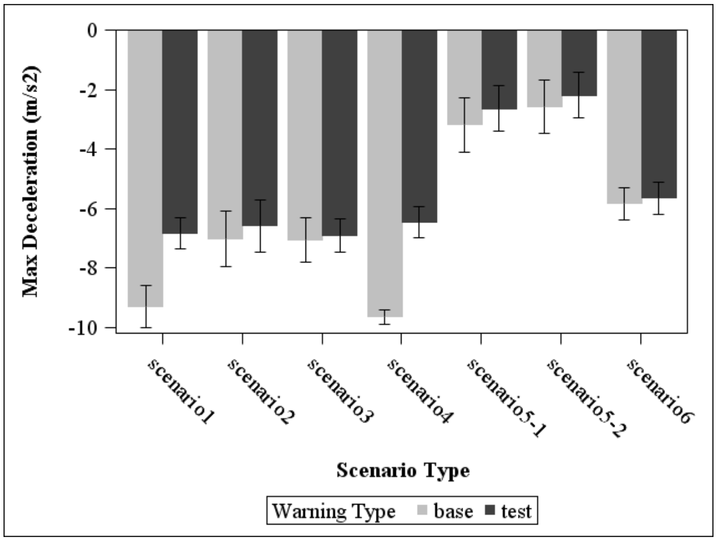


Figure 3.5 Max deceleration between the base and test conditions in each type of scenario

3.1.7 Maximum Brake Level

Regarding the max brake level (the maximum value is 180), in scenario 1 (“walk from behind adjacent car”) it was 66.84 in the test condition while it reached 149.75 in the base condition; the difference was statistically significant (p-value = 0.030). In scenario 2, the maximum brake level was similar (p-value = 0.134) between two conditions and it had a value between 80~95. In scenario 3 ("walk from behind right turning car"), the maximum brake level was significantly larger in the base condition

(96.86) than the test condition (80.46), with a p-value equals 0.09. Similarly, in scenario 4 ("walk from behind bush"), the max brake level was significantly larger in the base condition (149.50) than the test condition (65.47), with a p-value < 0.001. In scenarios 5 and 6, the maximum brake level was not significantly different (p-value > 0.1). Figure 3.6 shows the maximum brake between base and test conditions in each scenario.

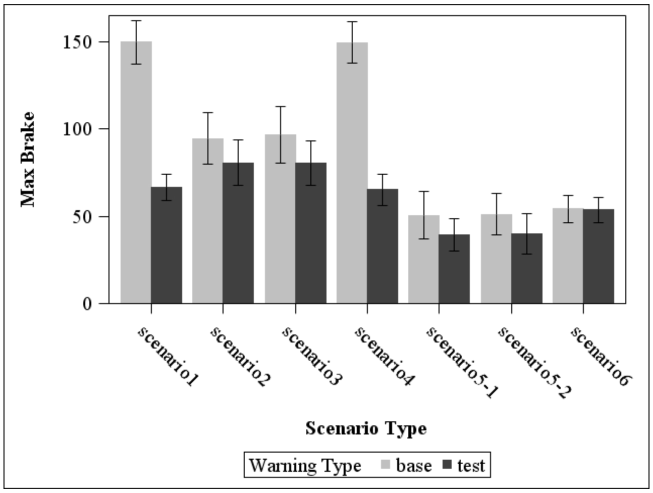


Figure 3.6 Max brake between the base and test conditions in each type of scenario

3.1.8 Jerk

Figure 3.7 shows the jerk between base and test conditions in each scenario. In general, the jerk was not significantly different between the base and test conditions in most scenarios. Only in scenarios 5-2 ("walk along curb-closer"), the jerk showed a significant difference between the two conditions. Specifically, the jerk was 18.70 in the test condition, while it was 37.42 in the base condition.

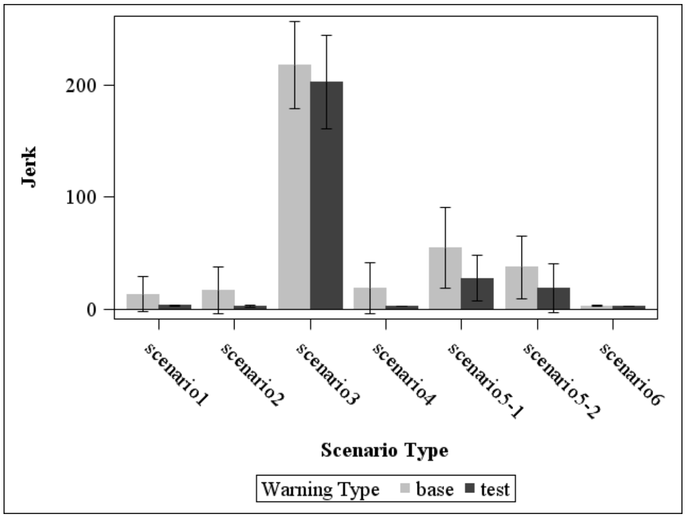


Figure 3.7 Jerk between the base and test conditions in each type of scenario

3.1.9 Stop Indicator

Figure 3.8 is the value of the stop indicator between base and testing conditions in each scenario. It shows that the stop indicator was significantly larger in the base condition than in the test condition in scenarios 1 (“walk from behind adjacent car”) and 4 ("walk from behind bush"). Specifically, in scenario 1, the stop indicator was 0.67 in the base condition, while it was only 0.47 in the test condition; the p-value is 0.086 and was at a significant level. In scenario 4, the stop indicator was 0.71 in the base condition, compared with only 0.42 in the test condition. For other scenarios, the stop indicator was not significantly different between conditions.

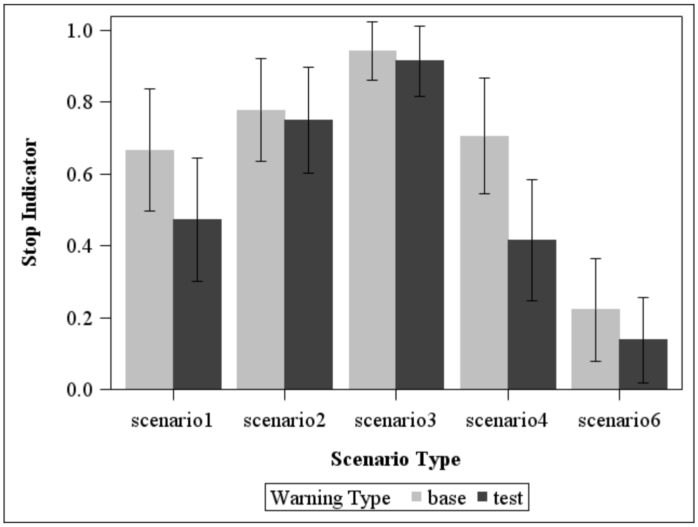


Figure 3.8 Stop Indicator between base and test conditions in each type of scenario

3.1.10 Minimum Distance

Figure 3.9 is the minimum distance between base and testing conditions in each scenario. Known from Figure 3-9, the minimum distance was significantly larger in the test condition than that in the base condition in scenarios 1(“walk from behind adjacent car”), 3("walk from behind right turning car") and 4 ("walk from behind bush"). Specifically, in scenario 1, the minimum distance in two conditions was 24.77m and 9.54m, respectively. The difference was significant (p-value = 0.0002). In scenario 3, the minimum distance was 24.83m in the test condition compared with 19.71m in the base condition, with a p-value equals to 0.09. In scenario 4, the minimum distance was 23.30m in the test condition, while it was 10.50m in the base condition; the difference was significant (p-value = 0.004). However, in other scenarios, the minimum distance was similar between the two conditions.

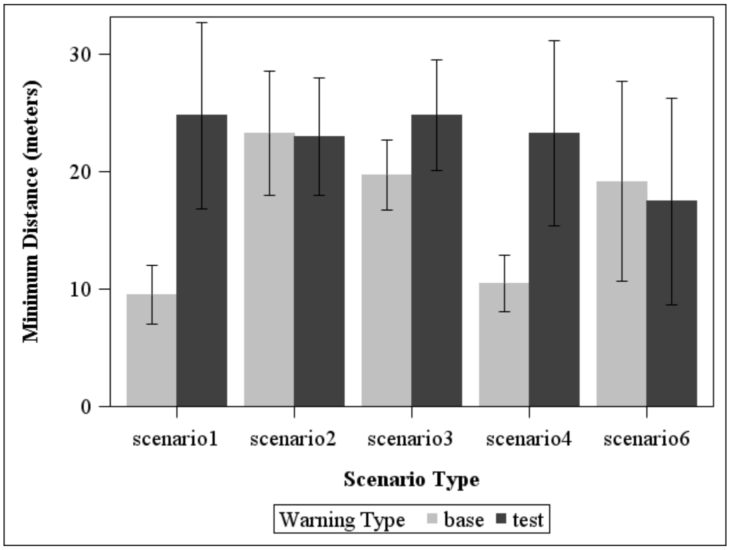


Figure 3.9 Minimum distance between base and test conditions in each type of scenario

3.1.11 Stopping Distance

Figure 3.10 shows the stopping distance between base and testing conditions in each scenario. In most scenarios, the stopping distance in the test condition was significantly larger than that in the base condition. Specifically, in scenario 1 ("walk from behind adjacent car"), the stopping distance was 43. 60m and 12.56m in the test and base conditions, respectively. The difference was significant (p-value < 0.001). In scenario 4 ("walk from behind bush"), the stopping distance was 45.29m and 13.24m in the test and base conditions respectively with a significant difference (p-value < 0.001). In scenario 6 ("observed crossing"), the test condition had a stopping distance of 78.53m, which is significantly larger (p-value = 0.061) than that in the base condition of 62.17m.

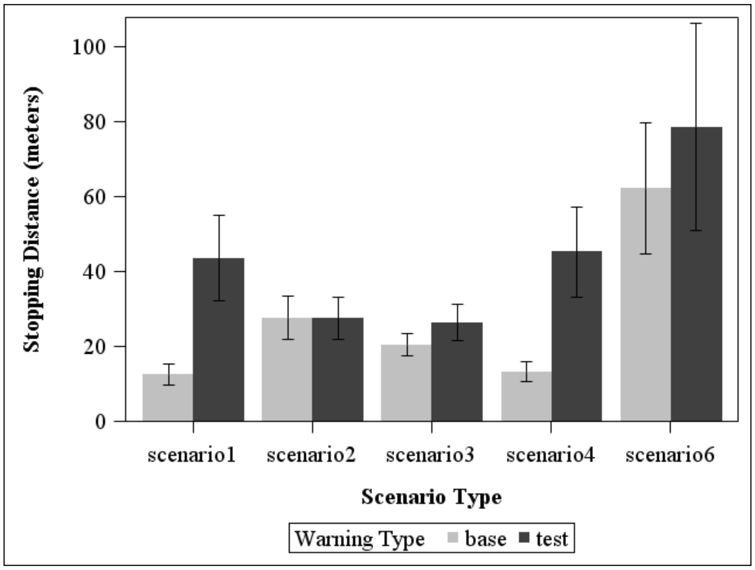


Figure 3.10 Stopping distance between base and test conditions in each type of scenario

3.2 The Interaction Effects of P2V System Related to Driver Features

3.2.1 Scenario 1

Figure 3.11 shows that in scenario 1 (“walk from behind adjacent car”), the BTMB was found significantly different (F=7.12, p=0.012) between drivers who have been involved in any not-at-fault crash in the last five years and those who have not. The test warning design significantly increased the BTMB for those drivers who have been involved in any not-at-fault crash before (F=17.73, p<0.01); while the effect of the base warning was similar between two groups of drivers. Specifically, the drivers who had not-at-fault crashes before had an average BTMB of 2.94 s under the test warning design, compared with a 1.24 s for drivers had not been involved in any not-at-fault crash before. A larger BTMB means the brake pedal was less heavy to press down, which means that the driver has a relatively gentle brake. Therefore, adopting a gradually changed warning design for drivers in this scenario could improve a driver’s brake performance, if the driver had any not-at-fault crash in the last five years.

Whether the driver has experience of using ADAS systems was also found to interact with the P2V system in terms of TRT in scenario 1 (F=4.16, p=0.049) (Figure 3-12). Not like the interaction effect from not-at-fault crash experience, in both two groups of drivers, the test P2V system design can significantly increase TRT compared with the base condition; however, the test design increased more TRT for drivers who had no ADAS experience before, i.e., an average increase from 0.32s to 1.16s. This indicates that the test design would be better to reduce the diving pressure for those new to ADAS.

The citation experience was found to be not interacted with the warning type on any of the driver performance variables in scenario 1.

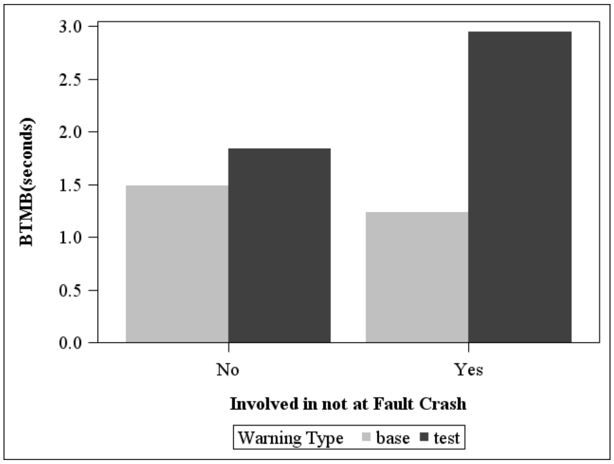


Figure 3.11 The effect of P2V system on BTMB between drivers of different not-at-fault crash experience in scenario 1

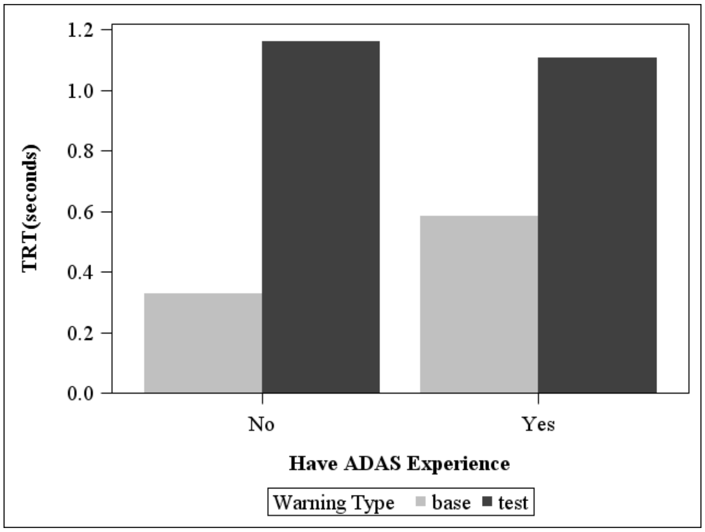


Figure 3.12 The effect of P2V system on TRT between drivers of different ADAS experience in scenario 1

3.2.2 Scenario 2

In scenario 2, whether the driver has ADAS experience significantly interacted with the P2V design on BRT (F=4.76, p=0.036). Further analysis shows that for drivers who have ADAS experience before, the BRT between two types of warning design was similar; while for drivers who did not have ADAS experience before, the test warning design can significantly reduce the BRT compared with the base warning design (F=3.66, p=0.064) (Figure 3.13). This indicates that the test warning design would be beneficial for novices to these new technologies.

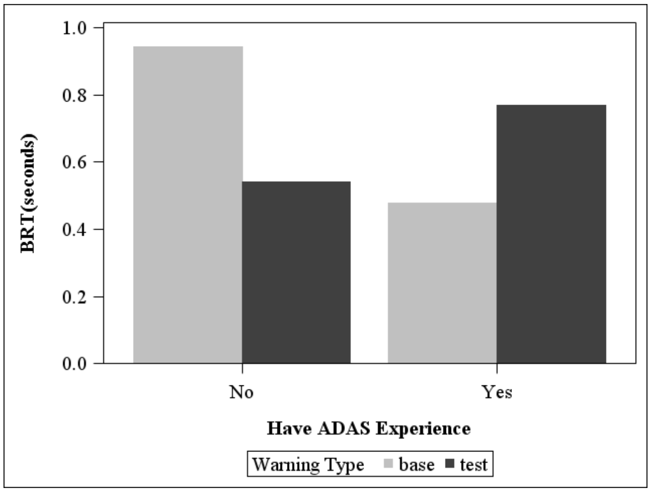


Figure 3.13 The effect of P2V system on BRT between drivers of different ADAS experience in scenario 2

In terms of the not-at-fault crash experience and the citation experience, no significant interaction effects on driver performance were found between these driver features and P2V system design.

3.2.3 Scenario 3

In scenario 3, the P2V design was found to interact with the not-at-fault crash experience on the maximum brake value (F=7.35, p=0.01) and jerk value (F=5.11, p=0.03) (Figures 3.14,15). For the maximum brake, statistical analysis shows that for drivers who had not been involved in any not-at-fault crash before, the test warning design significantly reduced the maximum brake level compared with the base warning design (F=9.53, p=0.004); however, for drivers who had not at fault crash experience, there was no significant difference between two types of warning design. Similarly, For the jerk, for drivers who had not been involved in any not-at-fault crash before, the test warning design significantly reduced the jerk level compared with the base warning design (F=3.10, p=0.008); however, for drivers who had not at fault crash experience, there was no significant difference between two types of warning design.

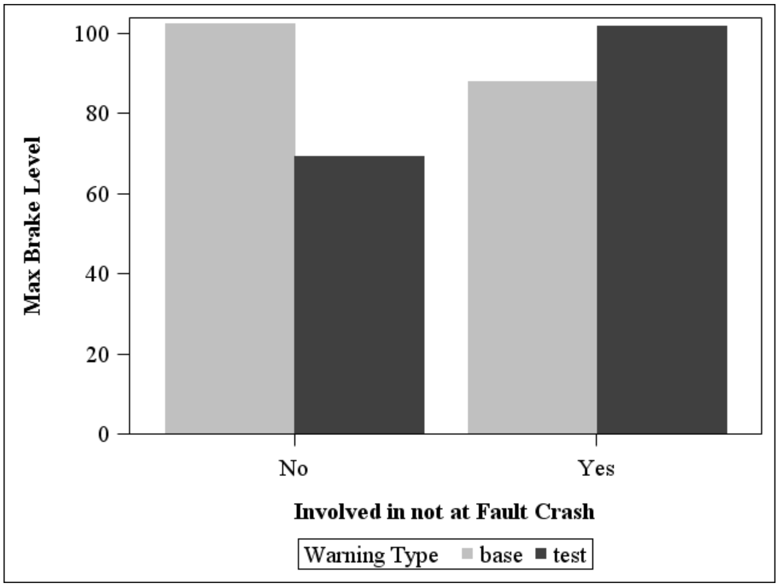


Figure 3.14 The effect of P2V system on maximum brake between drivers of different not at fault crash experience in scenario 3

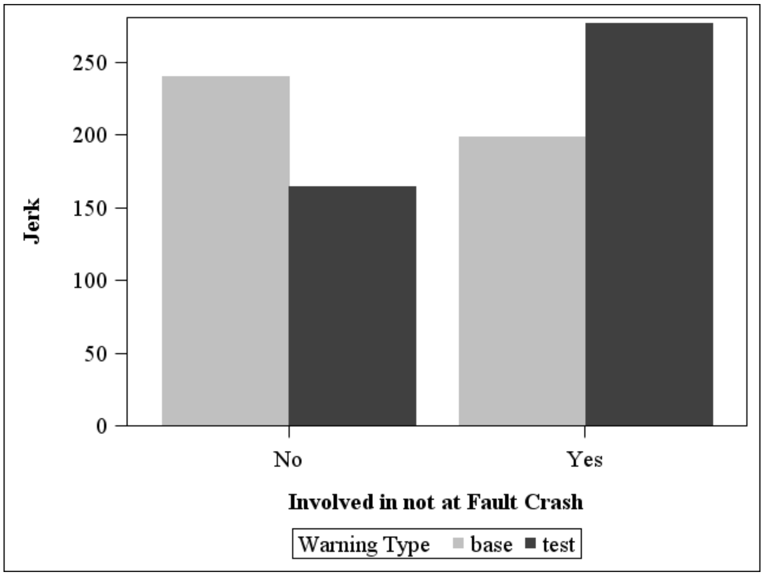


Figure 3.15 The effect of P2V system on the jerk value between drivers of different not at fault crash experience in scenario 3

In addition, the P2V design was found to interact with the ADAS experience on the maximum deceleration (F=10.03, p=0.003) (Figure 18) and jerk value (F=7.66, p=0.009) (Figure 3.16). For maximum deceleration, it was found that the interaction effect was significant for both two groups of drivers. However, the effect direction was the opposite. The test warning design reduced the deceleration for drivers who do not have ADAS experience, while it increased the deceleration for drivers who have ADAS experience. Similarly, as for the jerk, the test warning design significantly reduced the jerk (F=4.97, p=0.033) for drivers who do not have ADAS experience compared with the base warning design; but there was no significant difference between the test and base conditions for drivers who have ADAS experience.

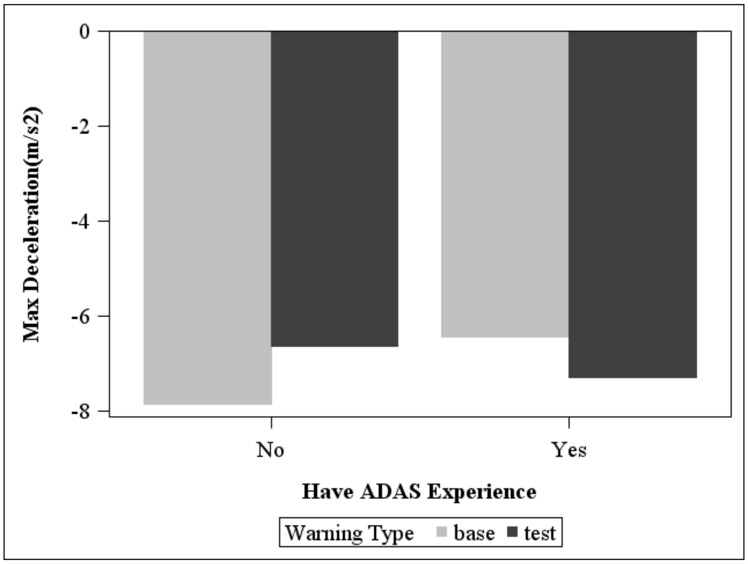


Figure 3.16 The effect of P2V system on the maximum deceleration between drivers of different ADAS experience in scenario 3

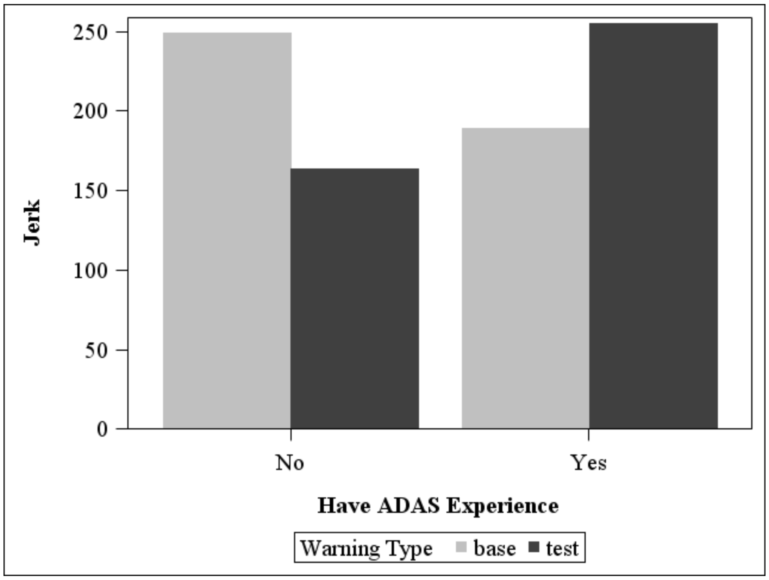


Figure 3.17 The effect of P2V system on the jerk between drivers of different ADAS experience in scenario 3

3.2.4 Scenario 5

Scenario 5 has two sub-scenarios. For sub-scenario 5-1, the TRT was found to be affected by the interaction effect of the P2V design and not at fault crash experience (F=5.25, p=0.029) (Figure 3.18); further analysis shows that drivers who have not been involved in not at fault crash before received a significantly lower throttle to release time under the test warning design; however, the difference between two types of P2V designs was not significantly different for drivers who have been involved in not at fault crashes before. Similarly, the TRT was also found to be affected by the interaction effect of the P2V design and ADAS experience (F=5.14, p=0.031) (Figure 3.19), and the test P2V system had a significantly lower TRT on drivers who do not have ADAS experience before compared with the base P2V system (F=8.10, p-value=0.008); while the difference between two types of P2V designs was not significantly different for drivers who have been involved in not at fault crashes before.

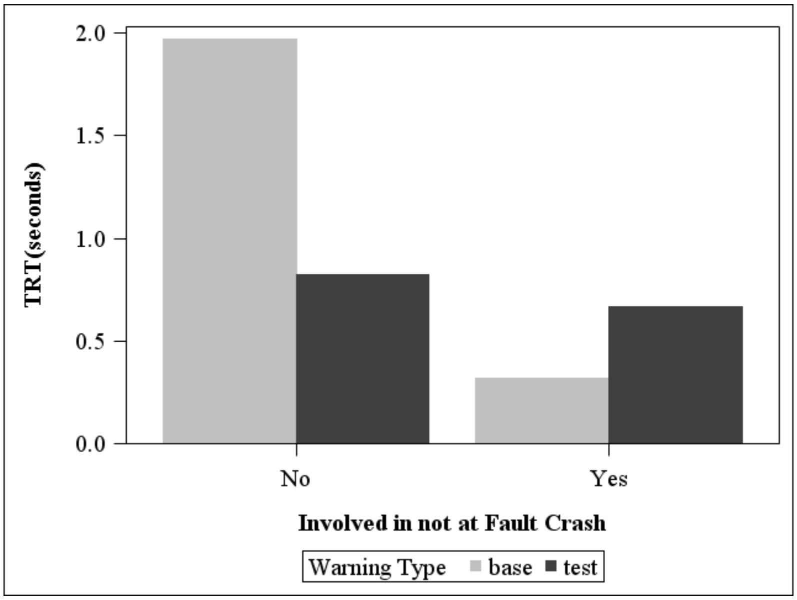


Figure 3.18 The effect of P2V system on the throttle to release time between drivers of different not at fault crash experience in scenario 5-1

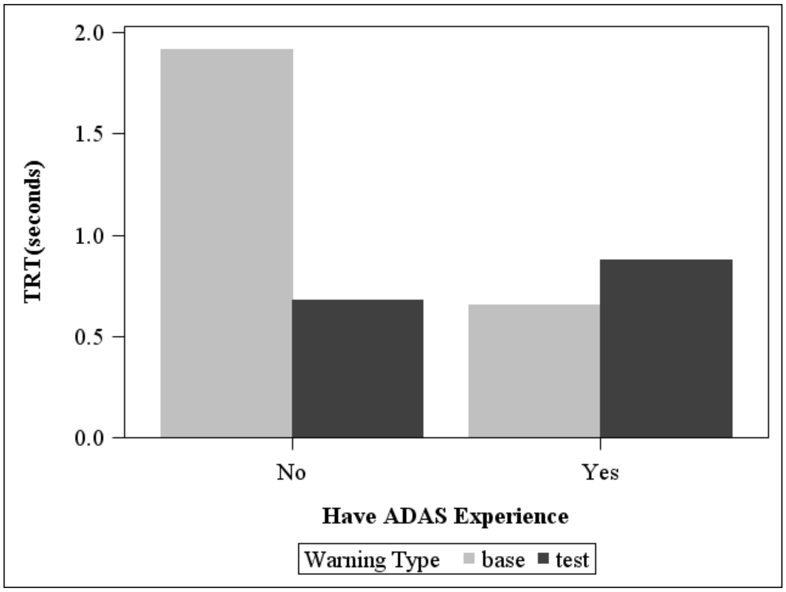


Figure 3.19 The effect of P2V system on the throttle to release time between drivers of different ADAS experience in scenario 5-1

However, no interaction effect was found between P2V system design and driver features in terms of the driver performances in sub-scenario 5-2.

3.2.5 Scenarios 4 and 6

No significant interaction was found between the driver features and P2V system design in these two scenarios.

Table 3.1 Metrics between base and test conditions in each scenario

		Scenario 1			Scenario 2			Scenario 3		
Metric	Condition	Value	F-value	p-value	Value	F-value	p-value	Value	F-value	p-value
BRT	test	1.81(0.73)	41.66	<0.001	0.64(0.66)	0.47	0.50	2.34(1.41)	28.2	<0.001
	base	0.84(0.40)			0.76(0.70)			0.88(0.54)		
TRT	test	1.14(0.40)	77.32	<0.001	0.48(0.69)	0.85	0.362	0.94(1.07)	4.11	0.05
	base	0.44(0.32)			0.35(0.43)			0.51(0.44)		
BTMB	test	2.24(1.33)	10.09	0.003	1.36(0.77)	0.08	0.783	11.00(7.62)	51.63	<0.001
	base	1.39(0.56)			1.31(0.59)			1.32(0.95)		
Mean Deceleration	test	-1.86(1.42)	93.84	<0.001	-3.35(1.98)	0.17	0.681	-0.88(0.23)	18.7	<0.001
	base	-5.04(1.81)			-3.53(2.08)			-1.32(0.71)		
Max Deceleration	test	-6.83(1.54)	28.83	<0.001	-6.59(2.62)	0.6	0.442	-6.90(1.60)	0.14	0.713
	base	-9.31(2.03)			-7.03(2.75)			-7.07(2.15)		
Max Brake	test	66.84(22.40)	168.78	<0.001	80.64(36.82)	2.36	0.134	80.46(37.44)	3.04	0.09
	base	149.75(34.08)			94.69(40.98)			96.86(46.00)		
Speed Deviation	test	15.65(2.13)	5.91	0.02	8.48(3.80)	1.01	0.323	14.64(1.91)	197.62	<0.001
	base	13.79(4.50)			9.19(3.84)			8.71(2.25)		
Jerk	test	3.01(1.34)	1.55	0.22	2.37(1.80)	1.91	0.176	202.82(121.70)	0.28	0.6
	base	13.31(43.88)			16.78(62.21)			217.86(114.12)		
Stop Indicator	test	0.47(0.51)	3.13	0.086	0.75(0.44)	0.09	0.768	0.91(0.28)	0.33	0.572
	base	0.67(0.48)			0.78(0.42)			0.94(0.24)		
Minimum Distance	test	24.77(23.44)	17.59	<0.001	23.01(14.74)	0.01	0.928	24.83(13.81)	2.99	0.093
	base	9.54(7.00)			23.28(15.56)			19.71(8.59)		
Stopping Distance	test	43.60(22.02)	46.92	<0.001	27.60(14.13)	0.01	0.924	26.33(13.49)	3.59	0.068
	base	12.56(6.56)			27.64(14.84)			20.50(8.19)		

4 Discussion and Conclusions

The base P2V design (emergency warning design) had a higher collision rate than the test P2V design (gradually changed P2V warning) in scenarios 1 (“walk from behind adjacent car”) and 4 ("walk from behind bush"); this might because the test P2V design could help the drivers make gradually adjustments (e.g., deceleration, lane changing) to the upcoming events, and they do not need to take aggressive evasive actions in a very short time. It is also demonstrated by the BRT (Brake Reaction Time) and TRT (Throttle to Release Time) in scenarios 1 and 4 that the BRT and TRT were significantly larger in the test P2V design condition than the base P2V design in these two scenarios; this shows that the driver, as explained before, did not take a sudden brake when they received the warning from the test P2V design since they had sufficient time to figure out where was the danger coming from. In addition, under the test P2V design, scenarios 1 and 3 ("walk from behind right turning car") had a larger BTMB and the scenario 3 also showed a larger BRT and TRT, which is supplemental to the evidence. Also, the test P2V design increased the minimum distance and stopping distance in these scenarios. The scenarios 1,3 and 4 all belong to a type of scenario in which the pedestrians cannot be unobserved due to obstruction in the drivers' sight of view; for these types of scenarios, the test P2V design provides a driver with sufficient time to figure out what and where is the danger source, and this might make a driver feel more comfortable compared with directly pushing a driver a "stopping" order without having them know what is happening.

Another priority of test P2V design (gradually changed P2V warning) in scenarios in which the pedestrian is hidden (such as scenarios 1,3 and 4), is that the test P2V design would smooth the driver's adaptation behavior which can improve the driving comfort. In scenarios 1,3 and 4, the mean deceleration, maximum deceleration, and maximum brake were lower in the test P2V design than the base P2V design (emergency warning design). The phenomenon indicates the driver thought they did not need to use a hard brake. In addition, the stop indicator in scenarios 1 and 4 was also lower under the test P2V design, this shows that more drivers did not have to stop to avoid a potential crash which less affected their normal driving.

Different from scenarios 1,3 and 4, the scenarios 5 and 6 belong to a type of scenario that the pedestrian can be clearly observed. In scenarios 5 and 6 the TRT was smaller in the test P2V design (providing additional information) condition than the base P2V design condition (without the P2V system). A smaller TRT means a driver releases the throttle quicker. Given that the pedestrian was observed by the driver and the risk situation was under the driver's control, the test P2V design make a driver become more conservative and alert even though the driver has no difficulty to monitor the pedestrian (the driver knew what possible risk situation would happen quite well). Another evidence is that in scenario 6, the stopping distance was larger in the test P2V design, which shows the safety margin was increased.

Providing additional distance information may also be good for improving driving comfort. The jerk in scenario 5-2 ("walk along curb-closer") was lower under the test P2V (providing additional information) design than the base P2V design (without the P2V system), which indicates that the test P2V design may have a better driving comfort by allowing drivers to have more time to adapt to the possible danger.

Different interaction effects between P2V design and driver features were found. In scenario 1, the test P2V design (gradually changed P2V warning) significantly increased the BTMB for drivers who had involved in a not-at-fault crash before compared with the base P2V design (emergency warning design). This indicates that the test P2V design may particularly improve the brake performance of drivers who had been involved in a not-at-fault crash before since these drivers do not have to take a hard brake. For drivers who did not have not-at-fault crash before, the test P2V design may improve their driving comfort by reducing the hard brake in scenarios 3 and 5; in scenario 3, the results show that the test P2V design (gradually changed P2V warning) reduced their maximum brake levels and jerk compared with the base P2V design (emergency warning design); and in scenario 5, the drivers under the test P2V design (providing additional information) had a lower TRT.

To summarize, in general, the test P2V design (including gradually changed warning and considering additional information) could make a driver better adapt to the critical pedestrian pre-crash scenarios; in addition, the effectiveness of the test P2V design could be further improved when considering the scenario and the drivers' features.

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