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Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V) Passenger and Freight Vehicle Applications to Enhance Safety and Efficiency in Coastal Evacuations

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DISCLAIMER

Abstract

Connected and automated vehicle (CAVs) technology has the potential to improve traffic efficiency and safety by providing advisories related to different traffic, road, and environmental conditions. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications are two key communication systems of connected vehicle technology. Previous research focusing on the use of CAVs technology during evacuation period lacks examining drivers' behavior in such situations. Therefore, this study aimed to investigate drivers' response and acceptance to the CAVs technology provided through V2I and V2V communications during a hurricane evacuation. A driving simulator experiment was designed (including two scenarios) and seventy-nine drivers from different age groups drove those scenarios. The first scenario was a base scenario with no warnings while the second scenario included three V2I warning messages and one V2V warning message. The V2I messages included rain warning, congestion warning and alternate route information whereas the V2V message was a warning regarding a potential rear end crash with the vehicle at front. The warnings were provided through both in-vehicle display and audio messages. The results indicated that around 90% drivers complied with V2I rain warning, V2V potential crash warning and V2I alternate route information whereas less than 50% drivers complied with the V2I congestion warning. It was found also that the rain warning resulted in lower average speed during rain, the congestion warning resulted in higher time-to-collision (TTC), and the V2V crash warning resulted in higher TTC compared to the situation where no warnings were provided, indicating safe traffic operation during the evacuation time. When providing an advisory through in-vehicle display and audio messages about an alternate route (with shortest path) that can be used during evacuation to avoid traffic congestion on the main road, it was found that 74 drivers (out of 79 drivers) took the alternate route while only 23 drivers did the same in the presence of dynamic message sign (DMS) only. After participating in the experiment more than 80% of the drivers reported that the provided V2I and V2V messages were extremely useful or useful. The insights gained from this research can help in the design and implementation of connected vehicle technologies to improve transportation systems' performance during critical events like hurricane evacuation.

Introduction

The cooperative forward collision Warning alerts the driver about risk of frontal collision that includes head-on collision with an oncoming vehicle and rear-end collision with a vehicle in the lane ahead [1] . This warning system uses cameras and radars to detect possible collision threats. Vehicle-to-Vehicle (V2V) communication is a significant enhancement and extension of this available system [2]. V2V is a crash-avoidance system that depends on the exchange of information (e.g., speed, heading, status of braking) between vehicles in nearby areas to alert drivers about potentially hazardous circumstances that could result in a crash. Using the V2V system, drivers can be informed whether the vehicle in front of them is braking, whether there is a vehicle in the blind spot or whether another vehicle that is not unseen is quickly approaching the next intersection [3]. The potential of vehicle-to-vehicle (V2V) communication to wirelessly communicate data regarding the location and speed of nearby cars offers significant promise in aiding in the prevention of collisions, reducing traffic congestion, and improving the environment [4]. Vehicle to Infrastructure (V2I) communication is a wireless communication system between vehicles and the infrastructure. It generates connectivity which enables exchanging information from vehicle to the roadway infrastructure or vice versa [5]. V2I technology can collect data related to weather advisories, traffic light, traffic congestion and then these data can be transmitted by the roadside devices to the drivers so that they can be aware of the upcoming situations and take actions accordingly.

During the evacuation process for natural disasters such as hurricane, wildfire etc., efficiency of the transportation network is one of the important factors to reduce the evacuation time and in turn, to minimize the loss of life as well as property damage. Previous studies investigated the benefits of Connected and Automated Vehicles (CAVs) technology (provided with V2I and V2V communications) in improving the performance of transportation system during evacuation [6, 7]. These prior works either used microsimulation or customized simulator to examine the network wise performance, ignoring driver behavioral factors. At this point, to maximize the benefits from such emerging technology in maintaining resiliency and efficiency of the coastal road network, it is necessary to gain better understanding regarding how drivers will interact with V2V and V2I advisories during emergency evacuation.

This study addresses this limitation by assessing how drivers interact with V2V and V2I advisories and by determining how these advisories impact traffic safety during emergency evacuation situations for hurricanes. A driving simulator experiment was employed to create road environments within which drivers' acceptances and responses to V2V and V2I warnings were observed.

Literature Review

Advanced Vehicular Technology in Traffic Safety and Efficiency

Forward collision warning (FCW) system is one of the advanced driver assistance systems which helps avoid rear-end collisions by detecting and warning drivers of potential dangers. To determine the safety benefit of behavior-based (BB) FCW system during an overtaking scenario of cyclist by a car, Kovaceva, Bärgman [8] conducted safety assessments on the crash data derived from naturalistic driving data. To estimate the risk of injury and fatality of the cyclists, crash frequency along with the injury risk model was employed. According to the assessment result, the BB FCW can reduce both injury and fatality by 43–94% and 53–96% respectively in comparison with no FCW.

Ma, Li [9] Investigated the FCW system in a driving simulation experiment by measuring utility, driving performance visual load and subjective evaluation for different warning modalities and stages. Simulation data, eye-tracking data and subjective evaluation data were collected. A total of 30 drivers (15 males and 15 females) aged between 21 and 31 years old participated in the driving simulation experiment. Three types of warnings were provided – auditory, visual (head-up display and dashboard) and tactile warning (vibrations in the seat). Multimodal warning refers to the combination of all these warning types. Additionally, there were two warning stages – collision warning and collision pre-warning. Time-to-collision (TTC) for these two stages were 3 s and 5 s, respectively. ANOVA results indicated that mean TTC was significantly different across the different warning types. Subjective evaluation for utility indicated the highest score for the multimodal warning, whereas the score for user experience was low. Multimodal warning also contributed to reduced reaction time in comparison of the other warning types. On the other hand, multi staged warnings performed better than the single-stage warning in terms of longitudinal car-following performance. However, trust and user experience were worse for multi staged warning.

Ali, Sharma [10] employed a driving simulator with 78 participants to examine the effects of a connected environment on driver behavior and safety. To achieve this, lane changing task, car following task and interaction with traffic lights and pedestrians were explored. Their scenarios included no driving assistance (information or suggestions to help with driving), continuous assistance, delayed assistance, and briefly lost communication. The results showed that drivers maintained larger TTC to the pedestrians as well as during car following in the presence of continuous driving assistance. Less yellow light running was observed as drivers received advisory information during interaction with traffic lights. However, in the case of delayed assistance and lost communication, safety margins deteriorated.

Brijs, Mauriello [11] used advanced driver assistance system (ADAS) to increase safety while a car is overtaking a cyclist. A new advanced driver assistance system (ADAS) was created to aid drivers during the process of overtaking cyclists using a multi-modal approach, incorporating a multi-step warning system. A total of 48 drivers were recruited to participate in a driving simulation experiment. The activation criteria for the ADAS were lateral clearance (LC) and time-to-danger (TTD). Two scenarios consisted of base scenario and scenario with ADAS, and drivers encountered three events of overtaking. LC was selected to study the lateral control of the vehicle and TTD was selected to examine the longitudinal control of the vehicle. The results showed that the system increased the lateral clearance during passing and time-to-danger during the overtaking. Overall, the ADAS system was successful in enhancing the safety and mobility of bicycles when cars overtake them. Participants were also satisfied with the system and mentioned it as positive towards traffic safety.

Budan, Hayatleh [12] examined the effect of V2I communication at unsignalized intersections by developing a traffic simulation framework in PTV VISSIM. The communication was between vehicle agent and intersection control agent. They compared the performance of unsignalized intersection control with signalized intersection control. The result of the comparison indicated that under First-Come-First-Served (FCFS) based vehicle scheduling, average fuel usage, average vehicle delays, and average queue length decreased by 42%, 96%, and 93%, respectively. However, the type of advisory or warning messages were not specified in this study.

Mohammed, Ke [13] studied the impact of V2I advisory messages on drivers' behavior at signalized intersections. They conducted a field test with two scenarios: approaching a green signal and approaching a red signal. Auditory messages were delivered, with "keep current speed" for scenario 1 and "signal will turn red" for scenario 2. The results indicated a reduction in maximum speed frequency and significant deceleration change within 50 meters of the intersection due to the messages. Speed changes differed significantly between the scenarios with and without V2I.

Using Red-Light Violation Warning (RLVW), Banerjee, Jeihani [14] tested the performance of 93 drivers in a driving simulator experiment. They compared driving performance with and without RLVW and found that drivers took significantly longer time to reduce speed when the warning was present, indicating sufficient time for speed adjustment. However, drivers exhibited aggressive speed reduction after receiving the warning. Yu, Bao [15] examined drivers' compliance with V2I speed-related suggestions during intersection maneuvers using a test track experiment with 32 participants. The results showed a 72% compliance rate with the V2I advisories.

To examine the effect of queue alert systems on traffic safety, Zhang, Shen [16] conducted a driving simulation study by using a variety of roadside alerts and auditory alerts in combination with driver types (normal, distracted, and drowsy drivers) as well as weather conditions (sunny and foggy). They discovered that drowsy drivers showed the worst performance in terms of TTC and that in-vehicle audio messages were more effective to increase drivers' safety. Bashir and Zlatkovic [17] developed queue warning application (Q-WARN) algorithm by using the latitude and longitude of freight vehicles and intersections. They tested the warning system in three test bed locations in Wyoming using VISSIM and observed less speed variation, less delay and increased TTC in the presence of queue warning system.

Li, Qiao [18] studied drivers' reaction towards lane changing signs and voice messages in work zone by recruiting 40 participants in a driving simulator experiment. The findings demonstrated that the drivers' ability to prepare ahead for lane change with the help of the provided messages led to a decrease in the amount of time needed to accomplish the maneuvers. Providing messages about work zone also helps to reduce the speed compared to the case of no messages. Combination of warning types helps to improve safety in work zone [19]. However, if over-communication takes place, the visual warning systems in the human machine interfaces (HMI) might also lead to longer off-road eye glance which is a potential safety concern [20].

Using different types of curve warning (curve sign only, one-time curve speed warning, guided warning throughout the entire course of curve) and considering different roadway, geometric and traffic condition, Wang, Wang [21] examined drivers' compliance with curve speed warning system (CSWS) in a driving simulator experiment with 30 participants. They evaluated the compliance with the speed while provided with curve warnings and found that male drivers' speed compliance improved in case of receiving guided message compared to receiving curve sign only and one-time curve speed warning. Regarding the female drivers, the curve sign only warning increased their speed compliance. Simeonov, Hsiao [22] designed a driving simulator experiment using CSWS where a total of 24 firefighters were recruited. The results indicated that the presence of CSWS reduced the number of abrupt stops as well as the distance traveled over the safety speed limits on the curve. McElheny, Blanco [23] examined the efficacy of curve warning devices using a field test with 48 participants. Three different methods of warnings were used in that study: no warning, audio, and visual warning, and push back through throttle (Force "lbf" push of the accelerator pedal toward the driver's foot) combined with audio and visual warning. Participants who received the warnings demonstrated faster brake and throttle reaction times (The time required for a participant to disengage their foot from the throttle pedal). Also, their curve-approaching-speed was closer to the given advisory speed compared to the ones who did not receive warnings. However, because many drivers were unable to notice the throttle push back, adding the push back had no noticeable impact on reaction times.

To understand the impact of fog warning on drivers' behavior and traffic safety, Chang, Li [24] conducted a driving simulator experiment based on road data from Beijing. They considered three different fog zones – clear zone, transition zone and fog zone - and four different warning configurations - no warning, On-Board Unit (OBU) warning, dynamic message sign (DMS), and both OBU and DMS. According to results, the chance of a longitudinal crash was higher in the situation where there was no warning, whereas it was lower in the scenario where the OBU warning was used. Li, Jia [25] indicated that fog warning system also helps drivers to decelerate earlier and better control their speed. In this regard, several prior studies revealed that speed was found to be lower in the presence of V2I warnings messages [26-28]. It might be beneficial if the fog warnings are combined with the advisory speed to reduce the drivers' speed significantly [29]. The advantage of reduced speed was also observed by providing motorcycle safety warning system [30] and other V2I warning messages in different road, environment, and traffic condition [31].

Advanced Vehicular Technology During Evacuation

Rahman et al. [32] investigated the impact of adaptive cruise control (ACC) on traffic safety during hurricane evacuation through developing a microscopic simulation model in SUMO. To calibrate the model, traffic data was collected for a section of highway during hurricane Irma evacuation in Florida. The surrogate safety measures used to evaluate the safety performance were TTC and deceleration rate to avoid a collision (DRAC). If TTC value was less than 1.5 seconds and maximum DRAC value was 3.30 ms^{-2} between the leading and following vehicle, it was identified as a potential collision. By setting the time headway greater than 1.2 seconds, they found about 49.7% reduction of potential traffic collision during evacuation if the market penetration of vehicles with ACC is 25%.

Rahman, Bhowmik [33] determined the contributing factors behind the crashes during the evacuation using matched case control study. Based on the location of the crash, they collected traffic data from two detectors in both upstream and downstream locations. The conditions considered were regular time, evacuation time and combination of both of these periods. Their results showed that the chance of traffic crash occurrence increases in the presence of high traffic volume in the upstream and high variation of speed in the downstream. It was recommended to warn the drivers about the situation to reduce the potential crash risks. Based on a panel mixed binary logit model on the combined data (evacuation and regular time), it was concluded that the chance of crash occurrence increases in general during the evacuation period compared to the normal condition.

Intersections such as at-grade intersections and grade-separated intersections can also get affected and become congested due to the evacuation procedure for any natural disaster. Chang and Edara [34] used autonomous reservation-based intersection control (AReBIC) to investigate its performance compared to the signal controller that is optimized for evacuation time. This algorithm assumes that there is continuous communication between roadside equipment (RSE) and on-board unit (OBU) in the vehicle. Vehicles make a request through this algorithm to pass towards their desired direction while approaching the intersection. The algorithm was applied in VISSIM for a subset of a simulation model which consisted of 8 cities and 4 counties in Virginia. The selected road network was in Virginia Beach close to the Atlantic Ocean. In the presence of AReBIC, about 80% reduction in delay was observed in addition to the increase of average speed by more than twofold. This resulted in the early arrival of the evacuee in their destination to get rid of the condition during hurricane such as flooding or high wind gusts.

Bahaaldin, Fries [6] determined the effect of connected vehicle technology for no-notice evacuations through a case study of a metropolitan area. No-notice evacuation includes the evacuation for earthquakes, nuclear disasters etc., to the contrary of short notice evacuation such as hurricane, wildfires, flooding etc. The authors of this study modeled the traffic during evacuation and the roadway network in VISSIM. Using varying market penetration rates (MPR), they measured average delays and total delays, and noticed significant reduction of delays at 30% MPR [6].

Rizvi, Olariu [35] examined the use of Vehicular Ad Hoc Networks (VANETs) to improve the efficiency of evacuation plans. The idea was to warn the drivers about approaching Emergency Service Vehicles (ESVs) such as ambulances, police cars, supply trucks, fire trucks during evacuation. VANETs are formed with vehicles which are equipped with wireless communication technology. The main purpose of VANET is to exchange messages related to traffic safety such as collision warning and other information. The results form that simulation study indicated the potential of VANETS to reduce the chaos in traffic situation during emergency scenarios [35].

Pu [7] used VANET to minimize the travel time during evacuation by integrating V2V and V2I communication. Using the V2I communication, the vehicle sends a request to the Road-Side Units (RSU) with its recorded travel time for different paths and RSU sends the updated travel times for those paths. Using these updated travel time, vehicle decides on the shortest path to reach the desired destination. Additionally, V2V communication was taken into consideration to allow the distant vehicles from RSU to update their shortest path using multi-hop relays. The results showed that evacuation time can be significantly reduced by using the proposed approach.

Gaps in Previous Studies

Most of prior studies related to evacuation were conducted using microsimulation analysis or survey studies. For example, Rahman, Hasan [32] conducted microscopic traffic simulation to investigate the usefulness of vehicles with ACC in reducing traffic collision during hurricane evacuation. Rahman, Bhowmik [33] also determined the lying factors behind crashes during evacuation based on matched case control study on traffic data. Bian, Murray-Tuite [36] examined peoples' behavior to phased evacuation strategy which focuses on stage wise evacuation rather than all at once. Using a behavioral intention survey among 450 households in a coastal area, they identified 66% of the evacuees would follow the phased evacuation order. These studies cover network-wise performance, determine factors behind traffic crashes as well as the use of advanced technology such as ACC in reducing disruptions during the evacuation period. However, individual drivers' behavior towards the connected vehicle messages regarding critical situations during evacuation time were not explored in any prior studies up to the authors knowledge. Therefore, it is important to understand how drivers would behave during evacuation periods if they were provided with warning/advisory messages through connected vehicle information technology such as V2V and V2I communications. The main objective of this study is to investigate drivers' response towards V2V and V2I messages during hurricane evacuation and to determine the effects of these warning messages on traffic safety.

Methodology

Scenario Design

To achieve these objectives, a driving simulator experiment was designed using the LSU driving simulator (Figure 1). The current LSU Driving Simulator is a full-sized passenger car (Ford Fusion) combined with a series of cameras, projectors, and screens to provide a high-fidelity virtual environment that offers a high degree of driving realism. It provides one degree of freedom motion simulation to make a driver experience similar driving efforts as in an instrumented vehicle. Its open architecture software tools allow for data collection during simulation experiments, and creation of new networks and virtually an infinite number of simulation scenarios.

Figure 1. LSU driving simulator.

The simulated road network consisted of a 4-lane divided highway and the total length of the simulated network was around 5.8 miles. The surrounding environment and the exits were designed to look similar to the segment of Louisiana I-10 East. The driving started from a local road to reach a shelter that was around 15 minutes away from the origin. At the beginning, drivers were informed through an audio message that a hurricane was coming and they were evacuating to reach a shelter. Then they were directed to merge to a highway. Throughout the driving, they encountered V2I rain warnings, V2V potential crash warning, V2I congestion warning and at the end, information for choosing alternate route through V2I communication. The information about the congestion, and the availability of alternate route can be received from sensors on the roads such as loop detectors. Also, the information about the rain can be retrieved from weather stations on the roads. Therefore, rain, congestion and alternate route information was classified as V2I communication. On the other hand, V2V warning is initiated by collecting braking or deceleration data of the front vehicle, therefore the potential crash warning was classified as V2V warning in this study. The methods and contents of these warnings/messages will be discussed in details in result section. Figure 2 shows some sections of the simulated roadways that participants drove in the driving simulator experiments.

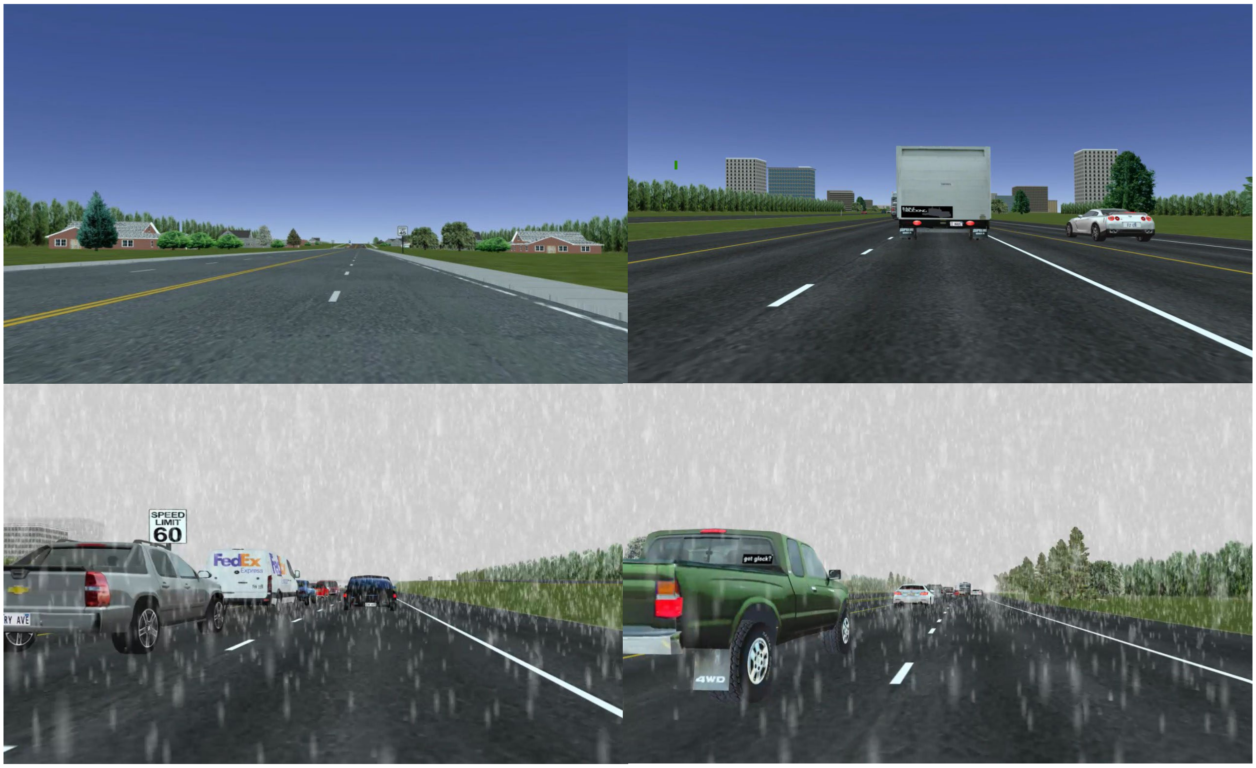

Figure 2. Some screen shots of the simulated roadway.

Procedures

Every participant was scheduled for a specific time slot to participate in this driving simulator experiment. The research team of this study explained the experiment to participants in brief upon arrival. Then, participants were asked to sign the consent form after reading some detail on the objectives of this research, their role in the experiment, how to participate, how the collected driving behaviors data will be used and will be kept anonymous, followed by filling up some background questionnaire and a before survey.

The participants were then led to the simulation car and then the experimenter explained how to start driving after adjusting the seat, mirrors etc. The experimenter asked the participants to push a red button located near the gear shift if they want to stop participating in the experiment due to any reasons such as feeling uncomfortable/motion sickness. Then, they were given around one minute to make sure that they are comfortable with the seat adjustment and air conditioning. Before starting the main experiment scenarios, each participant drove a warmup scenario for about 4 minutes to get used to the driving simulator such as making right and left turns, braking, lane changing, merging, taking exit etc. After that, they were randomly assigned to drive the tested scenarios in one of the following orders.

1. Base scenario with no warning followed by scenario with V2V and V2I warning messages.
2. Scenario with V2V and V2I warning messages followed by base scenario with no warning.

The experiment took approximately 28 minutes including the warmup driving. At the end, they filled up a post questionnaire survey indicating their opinion regarding the following warning messages they encountered while driving (Figure 3). The details of the contents of these warning messages will be discussed in the next section.

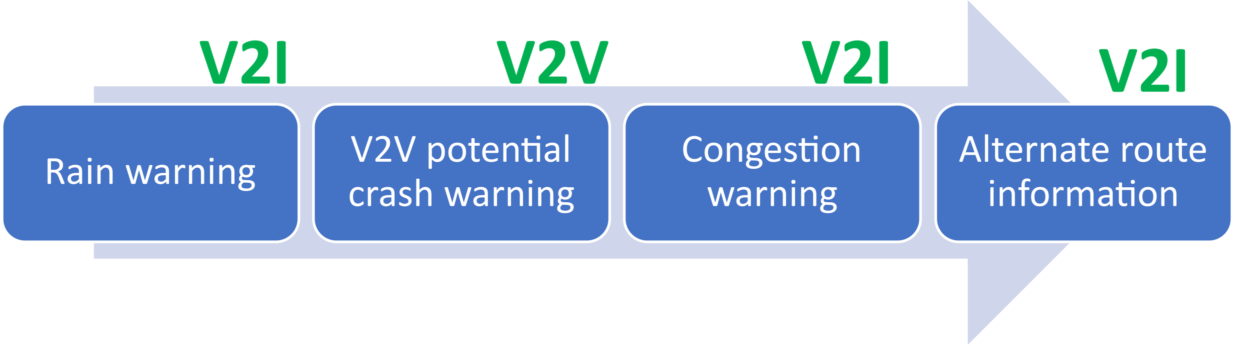

Figure 3. Type of warnings tested in this study.

Participants

A total of 121 licensed drivers who were at least 18 years old were invited to participate in the driving simulator experiment. However, due to the simulators motion sickness, 42 participants were not able to complete the whole experiment. Therefore, responses from a total of 79 participants were considered in the analysis of this study. Most of the participants who were not able to complete the experiments were from older age groups (+50 years old). Therefore, the participants mostly consist of drivers less than 50 years old. Only three participants were above 60 years old (One driver is from 60-64 years old and two drivers are above 65 years old). Table 1 shows the distribution of participants in the driving simulator experiment by gender and age. Among the 79 drivers, about 58% were male and 42% were female. Around 30% of these participants were from the 18-24 age group, 20.25% were from the 25-29 age group, 20.25% were form 30-34 age group. The percentage of drivers from age groups 35-39, 40-44, 45-49, 50 and above were 13.92%, 5.06%, 6.33% and 3.8%, respectively.

Table 1. Distribution of participants in the driving simulator experiment by gender and age

Category of Gender	Count	Percentage
Male	46	58.23%
Female	33	41.77%
Total	79	100%

Category of Age	Count	Percentage
18-24	24	30.38%
25-29	16	20.25%
30-34	16	20.25%
35-39	11	13.92%
40-44	4	5.06%
45-49	5	6.33%
50 and above	3	3.80%
Total	79	100%

Table 2 shows other demographic characteristics of the participants in this driving simulator experiment. Among the 79 drivers, around two-thirds had more than 5 years of driving experience and around three quarters did not get involved in a traffic crash. Around 55% have bachelor's degree or below and the rest have masters or doctorate degrees. A little more than 60% of the respondents drive less than 1 hour daily, around 8% don't drive daily, around 45% drive at most 3 days a week and around 55% of the participants drive at least 4 days a week. Around two-thirds defined themselves as average drivers and the rest defined themselves as safer than average drivers.

Table 2. Drivers' demographics.

Experience	Count	Percentages
Less than 2 years	9	11.39%
2 – 5 years	19	24.05%
More than 5 years	51	64.56%
Education		
High school/ college diploma /associate degree	21	26.58%
Bachelor's degree	22	27.85%
Master's degree	23	29.11%
Doctorate degree	13	16.46%

Crash Involvement		
Yes	19	0.240506
No	60	0.759494
DailyCommute		
0	7	8.86%
Less than 30 minutes	29	36.71%
30 minutes	20	25.32%
1 hour	17	21.52%
More than 1 hour	6	7.59%
DrivingDays		
0	7	8.86%
3 or less days	29	36.71%
4	20	25.32%
5	17	21.52%
6	5	6.33%
7	1	1.27%
Self-evaluation of driving style		
Safer than average	28	35.44%
Average	51	64.56%

Results

To investigate drivers' compliance with the various V2I and V2V warning messages mentioned above and to understand their impact on traffic safety from the designed driving simulator experiment, the following data were retrieved from the experiment.

For V2I warnings

1. Speed before rain warning
2. Speed after rain warning
3. Speed during rain
4. minTTC congestion
5. max Deceleration when approaching congestion.

For the V2V warning

6. Speed before V2V warning
7. Speed after V2V warning
8. Min TTC after V2V warning

To analyze the collected data, mixed linear model which includes both fixed and random effects were applied. The mixed model was applied through *proc glimmix* in SAS. Participant ID was considered as random factor and other variables including gender, age, experience, and the presence of warning were considered as the fixed factors in the analyses. The results from these analyses of the different scenarios examined in this study are described in the following section.

Rain Warning Scenario

To examine drivers' compliance with the V2I warnings, rain warnings were provided through in-vehicle display (Figure 4) and audio message ("There is raining ahead, please reduce your speed to 45 mph"). Figure 4 shows a screenshot of a participant driving through the rain weather conditions.

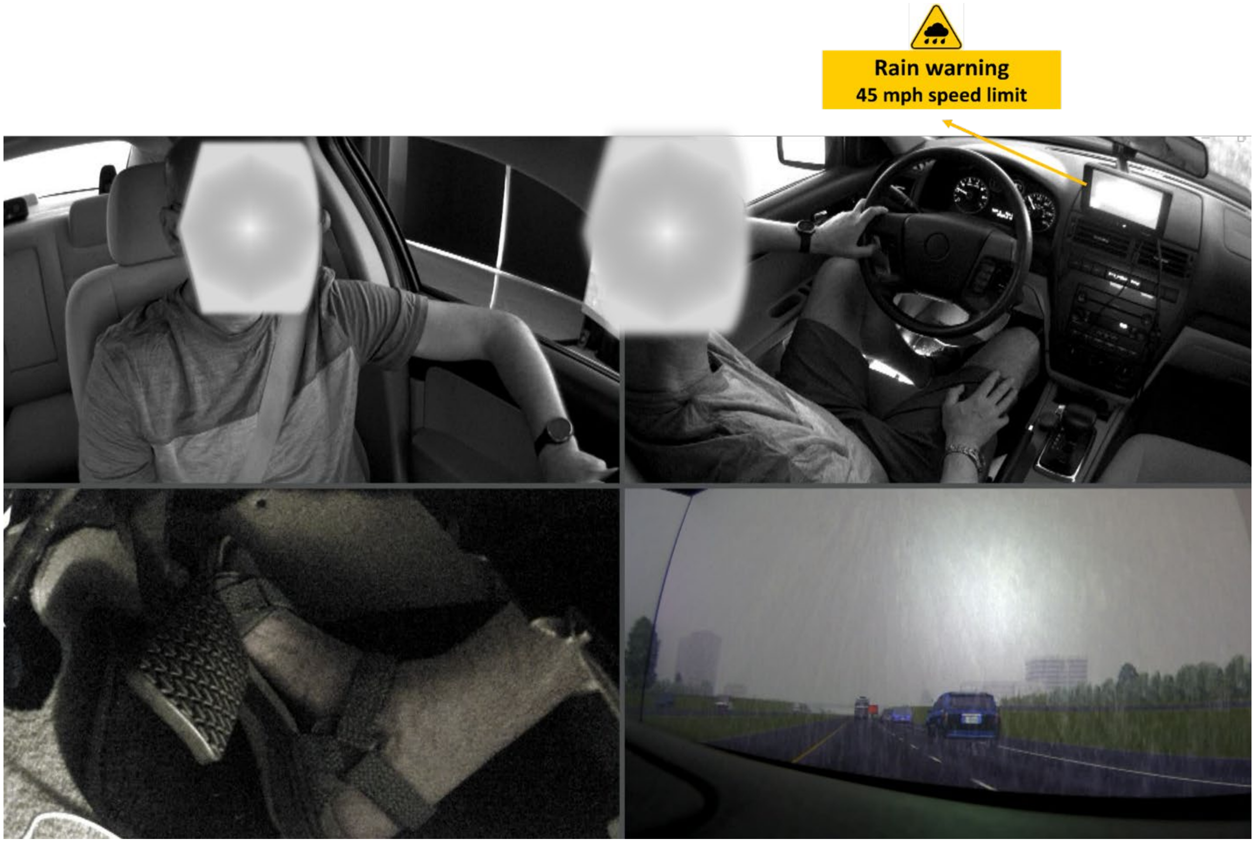

Figure 4. Rain warning scenario with the in-vehicle display warning for rainy weather.

Drivers' average speed was collected before and after providing the warning. Table 3 shows that 87.3% of the drivers complied with the rain warning by reducing their speed after receiving the warnings. Around 90% of the male participants complied with the rain warning, which is slightly lower for the female drivers (81.8%). In terms of age groups, the compliance rate with the warning increased in the higher age groups. The compliance was around 80% in the 18-24 age group, which increased to 93.8% in 25-29 age groups, to 87.5% in 30-34 age group, to 90.9% in 35-39 age group and to 91.7% in 40 and above age group. Similarly, highly experienced drivers showed more compliance with the rain warning. About 90% of the drivers with more than 5 years of experience showed compliance with the rain warning, whereas 82.1% of the drivers with 5 or less than 5 years of experience showed compliance by reducing their speed.

Table 3. Compliance rate with the rain warning.

Gender	Reduced speed		
	Yes	No	Total
Male	42 (91.3%)	4 (8.7%)	46
Female	27 (81.8%)	6 (18.2%)	33
Total	69 (87.3%)	10 (12.7%)	79

Age	Yes	No	Total
18-24	19 (79.2%)	5 (20.8%)	24
25-29	15 (93.8%)	1 (6.3%)	16
30-34	14 (87.5%)	2 (12.5%)	16
35-39	10 (90.9%)	1 (9.1%)	11
40 and above	11 (91.7%)	1 (8.3%)	12
Total	69	10	79

Experience	Yes	No	Total
5 and less	23 (82.1%)	5 (17.9%)	28
More than 5 years	46 (90.2%)	5 (9.8%)	51
Total	69	10	79

As shown in Table 4, the average speed before providing the rain warning message was around 58.16 mph which reduced to around 53 mph after receiving the warning (Table 4). The results of the mixed model analysis also indicated significant difference (F-value = 72.27, $p < 0.0001$) of speed before and after the warming at 95% confidence level (Table 5).

Drivers' average speed during rain was also lower when provided the warning (45.14 mph) compared to the no-warning scenario (55.62 mph). This result is in line with Li, Jia [25] which indicated that in the presence of fog warning, drivers were able to decelerate earlier and better control their speeds. The results of linear mixed model showed that the speed during rain was significantly lower (F-value = 172.58, $p < 0.0001$) in warning scenario. This means that presence of warning has significant effect on reducing speed during the rain. However, other independent factors (gender, age and experience) did not show any significant effect on the speed during rain. Both the minimum and maximum speed values during rain were also higher in no-warning scenario (Table 4).

Table 4. Statistics of rain warning scenario.

		Mean	Std Deviation	Median	Maximum	Minimum
Rain_compliance	Before warning	58.16	6.58	58.93	74.08	33.86
	After warning	53.08	6.4	53.7	71.6	37.57
Rain_speed	Warning	45.14	3.9	44.68	58.92	36.63
	No Warning	55.62	6.32	55.1	74.27	43.23

Table 5. Results of mixed model analysis of rain warning Scenario.

	Type III Tests of Fixed Effects				
	Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Rain compliance	Warning	1	70	72.27	<0.0001
Rain_speed	Warning	1	71	172.58	<0.0001

V2V Potential Crash Warning Scenario

After the rain warning scenario, drivers received a warning for a potential rear end crash with the vehicle at front. The audio warning was – *"A vehicle ahead is reducing speed, please reduce speed to avoid a potential crash"*. The in-vehicle display message and a screenshot of a participant pressing the brake pedal to avoid the crash are shown in Figure 5.

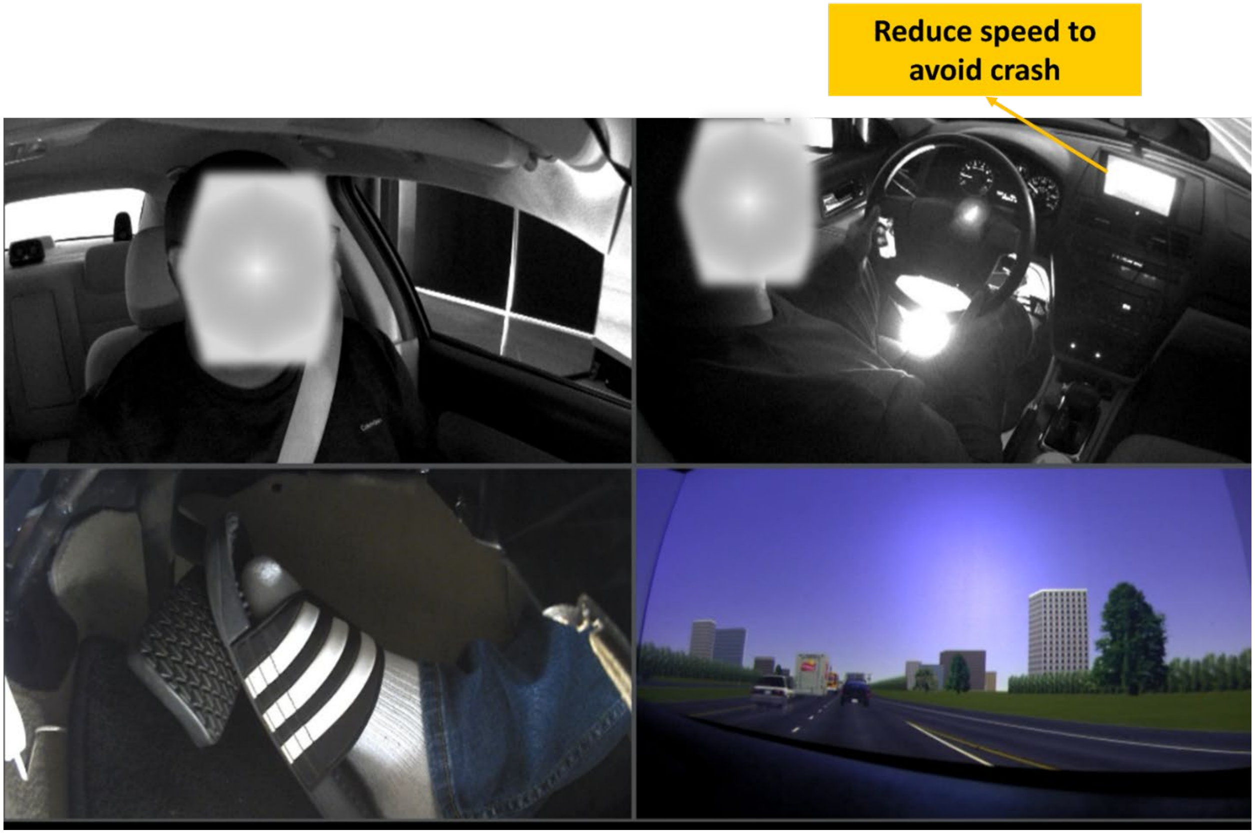

Figure 5. V2V potential crash scenario with the in-vehicle display warning.

According to Table 6, the compliance with the V2V potential Crash warnings was higher among the male drivers (89.1%) compared to the female drivers (81.8%). The compliance rates were higher among the 18-24 age group (91.7%) and 40 and above age group (100%). The compliance rates were 75%, 81.3% and 81.8% for 25-29, 30-34 and 35-39 age groups. Also, highly experienced drivers had higher compliance rate (88.2%) compared to the drivers with less driving experience (82.1%).

Table 6. Compliance rate with the V2V potential crash warning.

Gender	Reduced speed		
	Yes	No	Total
Male	41 (89.1%)	5 (10.9%)	46
Female	27 (81.8%)	6 (18.2%)	33
Total	68 (86.1%)	11 (13.9%)	79

Age	Yes	No	Total

18-24	22 (91.7%)	2 (8.3%)	24
25-29	12 (75%)	4 (25%)	16
30-34	13 (81.3%)	3 (18.8%)	16
35-39	9 (81.8%)	2 (18.2%)	11
40 and above	12 (100%)	0 (0%)	12
Total	68	11	79

Experience	Yes	No	Total
5 and less	23 (82.1%)	5 (17.9%)	28
More than 5 years	45 (88.2%)	6 (11.8%)	51
Total	68	11	79

Drivers were informed about the potential of a traffic crash as the front vehicle was reducing its speed. The speed after the warning was significantly lower (F-value = 23.12, $p < 0.0001$) at 95% confidence level (Table 8). The average speed was 52.76 mph before providing the warning which reduced to an average of 49.72 mph after providing the warning (Table 7). The minTTC was not significantly different (F-value = 0.38, $p = 0.544$) between these two scenarios. However, the higher mean minTTC value (17.56 seconds in warning vs 15.26 seconds in no warning) and higher median minTTC value (14.54seconds in warning vs 11.83 seconds in no warning) in Table 7 indicates improved traffic safety when providing the V2V warning about the potential of crash with front vehicle.

Table 7. Statistics of V2V potential Crash warning scenario.

		Mean	Std Deviation	Median	Maximum	Minimum
V2V_compliance	Before warning	52.76	8.66	52.39	76.21	36.32
	After warning	49.72	8.98	49.77	70.77	30.77
V2V_minTTC	Warning	17.56	8.73	14.54	34.81	5.60
	No Warning	15.26	8.86	11.83	33.76	4.13

Table 8. Results of mixed model analysis of rain warning Scenario.

	Type III Tests of Fixed Effects				
	Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
V2V_compliance	Warning	1	72	23.12	<0.0001
V2V_minTTC	Warning	1	27	0.38	0.544

Congestion Warning Scenario

The next V2I warning provided in the experiment was congestion warning. The warnings were provided through in-vehicle display (Figure 6) and audio message ("You may experience heavy traffic in your route"). Figure 6 shows a screenshot of a participant driving in a congested traffic condition.

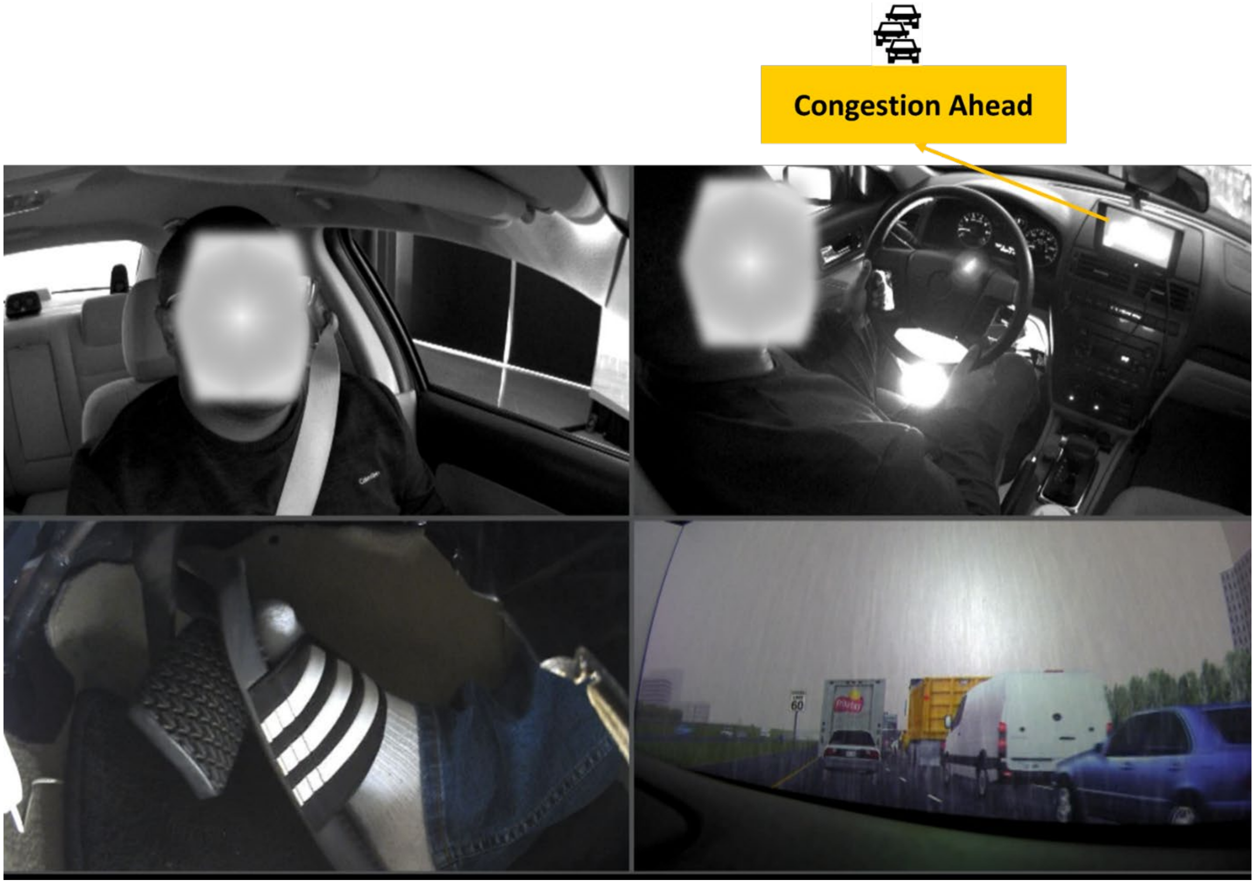

Figure 6. Congestion warning scenario with the in-vehicle display warning for congestion.

Drivers' average speed was collected before and after providing the warning to examine if drivers complied with the congestion warning by reducing speed after receiving the warning. Less than 50% of the participants responded to the warning by reducing speed (Table 9). The lowest compliance rate was among the participants from 40 and above each group (33.3%), followed by the 25-29 age group (37.5%), 35-39 age group (45.5%), 18-24 age group (45.8%) and 30-34 age group (62.5%) with the highest compliance rate. Also, drivers with less experience showed higher compliance with the congestion warning.

Table 9. Compliance rate with the congestion warning.

Gender	Reduced speed		
	Yes	No	Total
Male	23 (50%)	23 (50%)	46
Female	13 (39.4%)	20 (60.6%)	33
Total	36 (45.6%)	43 (54.4%)	79

Age	Yes	No	Total
18-24	11 (45.8%)	13 (54.2%)	24
25-29	6 (37.5%)	10 (62.5%)	16
30-34	10 (62.5%)	6 (37.5%)	16
35-39	5 (45.5%)	6 (54.5%)	11
40 and above	4 (33.3%)	8 (66.7%)	12
Total	36	43	79

Experience	Yes	No	Total
5 and less	15 (53.6%)	13 (46.4%)	28
More than 5 years	21 (41.2%)	30 (58.8%)	51
Total	36	43	79

Table 10 shows the maximum deceleration (maxDec) and minTTC after providing the congestion warning in warning scenario and also from the same location of no-warning scenario. Table 11 displays no significant difference (F-value = 1.04, *p =0.312*) in maxDec between these two scenarios. The average minTTC was higher by 2.02 seconds in the warning scenario. Also, the median value of minTTC was around 43% higher in the presence of congestion warning. Though these differences are not significant (F-value = 1.39, *p =0.244*) based on the mixed model analysis (Table 11), overall improved traffic safety was noticed, as higher minimum TTC represents higher traffic safety. This result is in line with Bashir and Zlatkovic [17], who found increased TTC in the presence of queue warning system. Though no main effect was found for warning and other demographic factors (gender, age and experience), a significant interaction effect (F-value = 4.8, *p =0.033*) between warning and gender was found. In the no-warning scenario, female had around 36% higher TTC than the male drivers. On the other hand, male had around 18% higher TTC than the female drivers.

Table 10. Statistics of congestion warning scenario.

		Mean	Std Deviation	Median	Maximum	Minimum
Congestion_maxDec	Warning	-0.018	0.012	-0.016	-0.058	-0.003
	No Warning	-0.017	0.015	-0.011	-0.063	-0.003
Congestion_minTTC	Warning	13.58	6.72	12.75	29.1	1.1
	No Warning	11.56	7.12	8.90	29.13	0.62

Table 11. Analysis results of congestion warning variables.

	Type III Tests of Fixed Effects				
	Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Congestion_maxDec	Warning	1	72	1.04	0.3120
Congestion_minTTC	Warning	1	58	1.39	0.244
	Warning*Gender	1	58	4.8	0.033

Alternate Route Information Scenario

After the congestion scenario, drivers were given information about an alternate route with shortest path to reach to their destination. In the no-warning scenario, drivers received the information only through a dynamic message sign (DMS) as shown in Figure 7. Drivers were explained beforehand that if they see a DMS stating time required through an exit and through the straight route, that means it will take 5 minutes to reach to their destination through the next available exit and 10 minutes through the existing straight route. In addition to the DMS, an in-vehicle display message and audio message ("within half a mile, you may take exit 157B to avoid congestion ahead or stay on the current route") were provided in the warning scenario. Figure 8 shows a screenshot of a participant driving while received the alternate route information in the in-vehicle display.

Figure 7. The DMS provided to show alternate routes

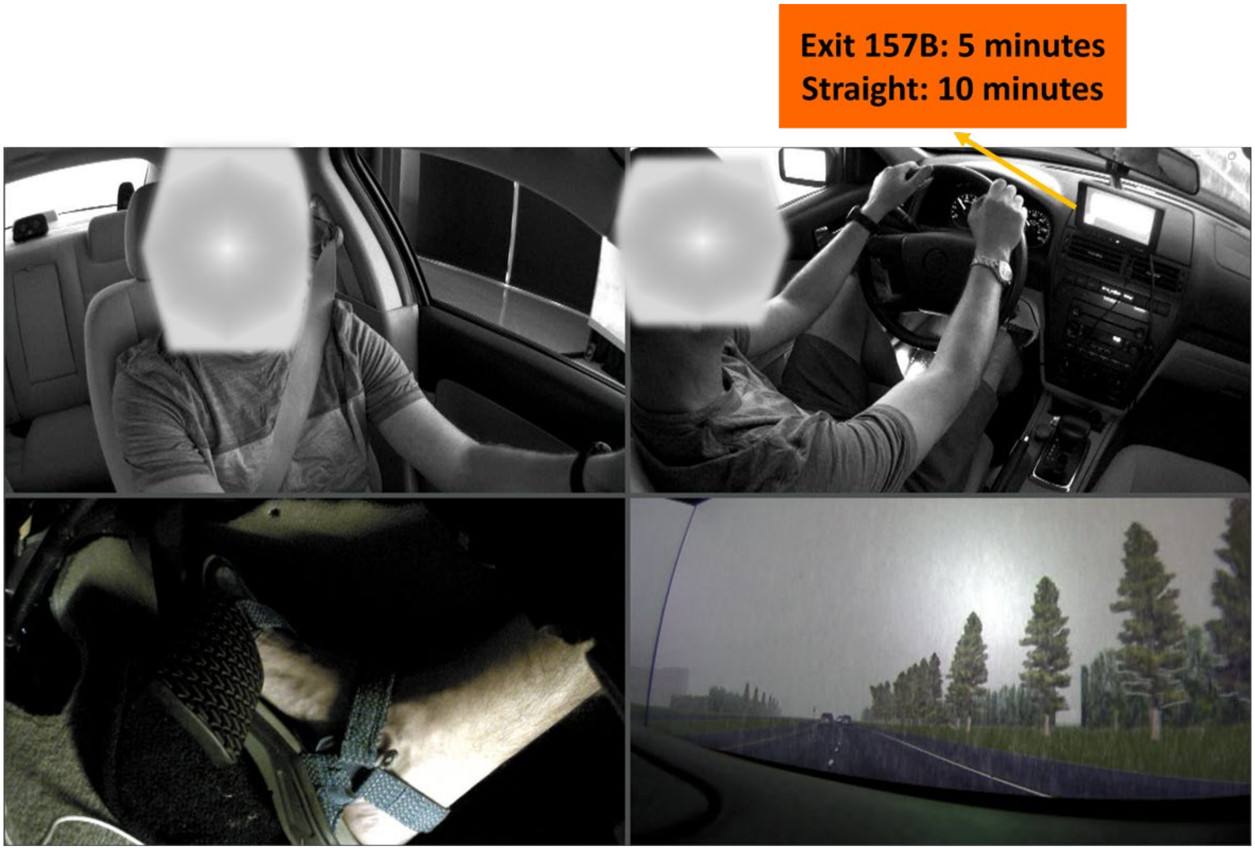

Figure 8. Alternate route information scenario with the in-vehicle display warning.

When in-vehicle display and audio messages were provided in addition to the DMS, 74 drivers (93.7% of participants) decided to take the alternative route to avoid congestion ahead and took the exit to reach their destination. However, 5 drivers (6.33% of participants) chose the current straight route. However, in the presence of only DMS in the no-warning scenario, only 23 drivers (29.11% of participants) took the exit. The remaining 56 drivers (70.89% of participants) continued straight to reach to their destination. As taking the exit is supposed to contribute to earlier arrival (5 minutes through the exit vs 10 minutes through straight route), these results indicate that the presence of in-vehicle display message and audio message through V2I communication in the warning scenario was helpful to take better decision during the hurricane evacuation. Descriptive statistics showed that among the 23 drivers, around 26% of the male drivers took exit in the presence of DMS, whereas 33.3% of the female drivers did so in the similar situation. In terms of age group, the percentage of the drivers taking exit in the presence of DMS only was higher with the increase of age.

Drivers' Opinion Regarding the V2I and V2V Warnings Messages

Before and after participating in this experiment, drivers were asked about their opinion on receiving the above-mentioned warnings messages during evacuation. Figure 9 shows that combined percentages of drivers who viewed the provided warning messages as extremely useful or useful are highest for V2I alternate route information (93.67%), followed by V2V potential crash warning (91.14%), V2I congestion warning (87.34%) and V2I rain warning (73.42%). After the participation, these percentages decreased by 1.27% for V2I alternate route information, decreased by 2.53% for V2V potential crash warning, increased by 6.33% for V2I congestion warning and increased by 7.59% for rain warning. Though the percentages decreased slightly for V2I alternate route information and V2V potential crash warning, they were still above 90% (92.41% for V2I alternate route information and 88.61% for V2V potential crash warning). Overall, more than 80% of the drivers mentioned the V2I and V2V warning messages as either useful or extremely useful after driving the experiment. Before participation, around 20% of the drivers were neutral about the usefulness of V2I rain warning, followed by 12.66% for V2I congestion warning, and 3.8% for both V2V potential crash warning and V2I alternate route information. These percentages did not change much after the participation except for congestion warning (decreased by around 9%). Very few drivers thought these warning messages as not useful and not useful at all.

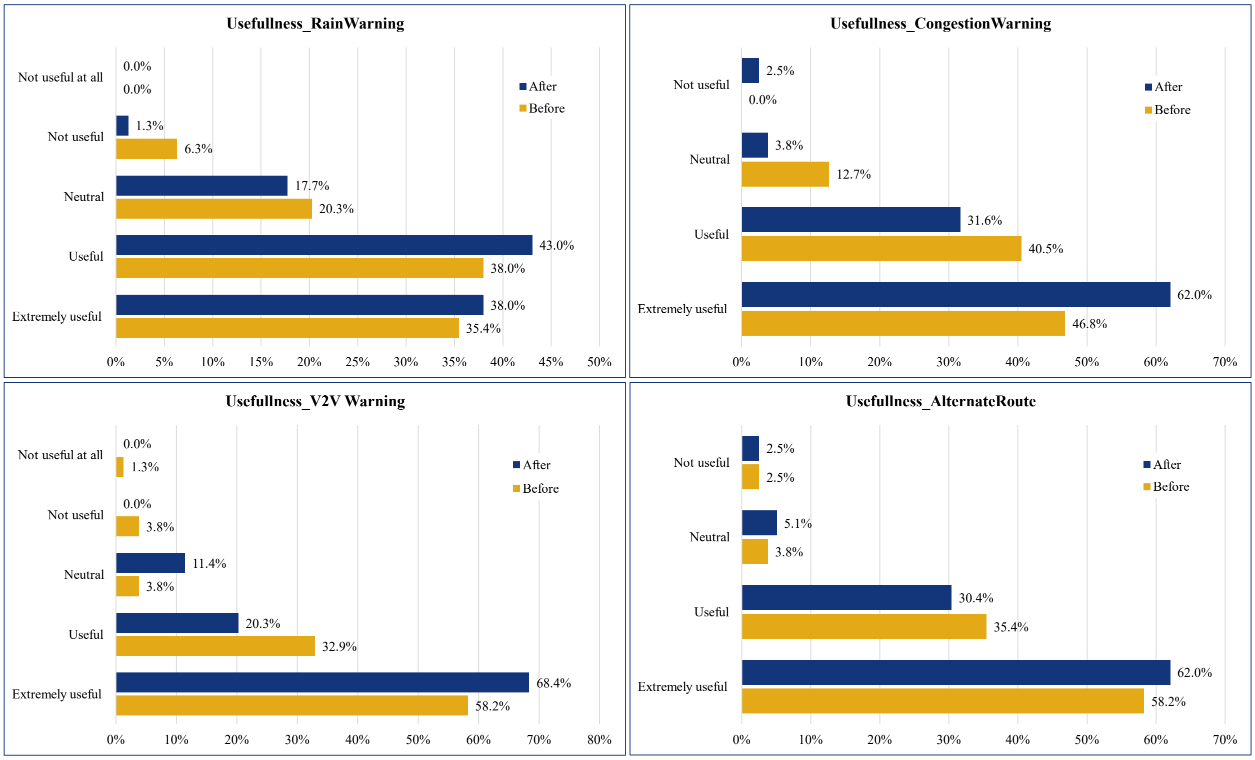

Figure 9. Drivers' opinion on the usefulness of different V2V and V2I warning messages.

Conclusions and Recommendations

This study aimed to investigate drivers' compliance with different V2I and V2V warning messages during evacuation (e.g., due to hurricane) and the impact of these warning messages on traffic safety. A driving simulator experiment was designed to examine drivers' acceptance and responses to various V2I and V2V warning messages. Four warnings/advisory messages were examined in the driving simulator experiment including V2I warning/advisory regarding rain, traffic congestion, alternative route to shelter and V2V warning about a potential crash. The results indicated that the overall compliance rates of drivers were 87.3%, 45.6%, 93.7% and 86.1% for the rain warning, congestion warning, alternate route information and potential V2V crash warning, respectively. Also, the speed was significantly lower during the rain when the V2I rain warning was provided. This means that V2I rain warning can help in improving traffic safety during rainy weather by reducing drivers' speed. It was found that only 45% of drivers complied with the V2I congestion warning. This might be because drivers do not want to reduce speed until they observe the congestion. Nevertheless, the V2I congestion warning helped to improve safety by contributing in higher TTC. In case of V2V rear end crash warning, the TTC was higher compared to the situation when no warning was provided. This suggests that V2V warning about a potential crash during evacuation time can help improving safety by reducing the probability of crashes.

Regarding providing an advisory message about an alternative route for early arrival to their destination (shelter to evacuate from a hurricane) to avoid congestion in the main road, providing V2I messages through in-vehicle display and audio messages along with the dynamic message signs (DMS) resulted in more drivers taking the alternative route than when providing the advisory through DMS only. These results suggest that the presence of alternate route information through V2I communication during hurricane evacuation can help drivers to choose the shorter path and in turn can improve the efficiency of the road network by reducing traffic congestion in the main highway. Regarding drivers' opinion about these V2I and V2V warning messages, more than 80% drivers reported that these messages are useful or extremely useful after participating in the driving simulator experiment. This indicates that drivers are willing to comply with the V2I and V2V warning messages during the evacuation time since these messages would help to improve traffic operation and safety during such critical conditions.

These findings provide valuable information regarding drivers' responses as well as their opinions regarding the connected vehicle warning messages via V2I and V2V communications. This can help transportation authorities to tolerate their plans and guidelines to maximize the benefits from V2V and V2I implementation especially during evacuation. Such understanding will be helpful as well for developing guidelines related to CAVs to enhance disaster planning in coastal regions. This study investigated the usefulness of four different V2I and V2V warning/advisory messages during hurricane evacuation. The warnings were provided through both in-vehicle display and audio message. Future studies are recommended to examine if providing one type of warning (auditory message only or in-vehicle display message only) would be effective to achieve these benefits. Incorporating different contents of the warning messages may also provide additional insights.

References

1. Andrews, S., *Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) Communications and Cooperative Driving*, in *Handbook of Intelligent Vehicles*, A. Eskandarian, Editor. 2012, Springer London: London. p. 1121-1144.
2. Chitanvis, R., et al. *Collision avoidance and Drone surveillance using Thread protocol in V2V and V2I communications*. in *2019 IEEE National Aerospace and Electronics Conference (NAECON)*. 2019.
3. USDOT. *Vehicle-to-vehicle communication technology*. Available from: https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/v2v_fact_sheet_101414_v2a.pdf.
4. NHTSA. *Vehicle-to-vehicle communication*. Available from: https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication.
5. FHWA, *Crash Data Analyses for Vehicle-to-Infrastructure Communications for Safety Applications*. 2012, University of North Carolina Highway Safety Research Center.
6. Bahaaldin, K., et al., *A Case Study on the Impacts of Connected Vehicle Technology on No-Notice Evacuation Clearance Time.* Journal of Advanced Transportation, 2017. **2017**: p. 6357415.
7. Pu, C. *Evacuation Assisting Strategies in Vehicular Ad Hoc Networks*. in *2018 9th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON)*. 2018.
8. Kovaceva, J., J. Bärgman, and M. Dozza, *On the importance of driver models for the development and assessment of active safety: A new collision warning system to make overtaking cyclists safer.* Accident Analysis & Prevention, 2022. **165**: p. 106513.
9. Ma, J., J. Li, and H. Huang, *Evaluation of Multimodal and Multi-Staged Alerting Strategies for Forward Collision Warning Systems.* Sensors, 2022. **22**(3): p. 1189.
10. Ali, Y., et al., *The impact of the connected environment on driving behavior and safety: A driving simulator study.* Accident Analysis & Prevention, 2020. **144**: p. 105643.
11. Brijs, T., et al., *Studying the effects of an advanced driver-assistance system to improve safety of cyclists overtaking.* Accident Analysis & Prevention, 2022. **174**: p. 106763.
12. Budan, G., et al., *An analysis of vehicle-to-infrastructure communications for non-signalised intersection control under mixed driving behaviour.* Analog Integrated Circuits and Signal Processing, 2018. **95**(3): p. 415-422.
13. Mohammed, M., et al., *Connected vehicle v2i communication application to enhance driver awareness at signalized intersections*, in *CSCE Annual Conference*. 2016, Resilient Infrastructure: London.
14. Banerjee, S., et al., *Influence of red-light violation warning systems on driver behavior – a driving simulator study.* Traffic Injury Prevention, 2020. **21**(4): p. 265-271.
15. Yu, B., et al., *Examination and prediction of drivers' reaction when provided with V2I communication-based intersection maneuver strategies.* Transportation Research Part C: Emerging Technologies, 2019. **106**: p. 17-28.
16. Zhang, Z., et al. *Implementation and Performance Evaluation of In-vehicle Highway Back-of-Queue Alerting System Using the Driving Simulator*. in *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*. 2021.

17. Bashir, S. and M. Zlatkovic, *Assessment of Queue Warning Application on Signalized Intersections for Connected Freight Vehicles.* Transportation Research Record, 2021. **2675**(10): p. 1211-1221.
18. Li, Q., F. Qiao, and L. Yu, *Socio-demographic impacts on lane-changing response time and distance in work zone with Drivers' Smart Advisory System.* Journal of Traffic and Transportation Engineering (English Edition), 2015. **2**(5): p. 313-326.
19. Li, J., et al., *Assessment of In-Vehicle Messages in the Advance Warning Area of a Work Zone.* Journal of Civil & Environmental Engineering, 2018. **08**.
20. Raddaoui, O. and M.M. Ahmed, *Evaluating the Effects of Connected Vehicle Weather and Work Zone Warnings on Truck Drivers' Workload and Distraction using Eye Glance Behavior.* Transportation Research Record, 2020. **2674**(3): p. 293-304.
21. Wang, S., et al., *Guidance-oriented advanced curve speed warning system in a connected vehicle environment.* Accident Analysis & Prevention, 2020. **148**: p. 105801.
22. Simeonov, P., et al., *Evaluation of advanced curve speed warning system for fire trucks.* Applied Ergonomics, 2021. **97**: p. 103527.
23. McElheny, M., M. Blanco, and J.M. Hankey, *On-Road Evaluation of an In-Vehicle Curve Warning Device.* Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2006. **50**(22): p. 2414-2418.
24. Chang, X., et al., *Evaluation of cooperative systems on driver behavior in heavy fog condition based on a driving simulator.* Accident Analysis & Prevention, 2019. **128**: p. 197-205.
25. Li, X., et al., *Safety Evaluation of Fog Warning Systems in a Connected Vehicle Environment Based on Sample Entropy.* Journal of Advanced Transportation, 2021. **2021**: p. 3047756.
26. Böhm, M., et al., *Driver Behavior and User Acceptance of Cooperative Systems Based on Infrastructure-to-Vehicle Communication.* Transportation Research Record, 2009. **2129**(1): p. 136-144.
27. Ahmed, M.M., G. Yang, and S. Gaweesh, *Assessment of Drivers' Perceptions of Connected Vehicle–Human Machine Interface for Driving Under Adverse Weather Conditions: Preliminary Findings From Wyoming.* Frontiers in Psychology, 2020. **11**.
28. Zhao, X., et al., *A study of the compliance level of connected vehicle warning information in a fog warning system based on a driving simulation.* Transportation Research Part F: Traffic Psychology and Behaviour, 2021. **76**: p. 215-237.
29. Raddaoui, O., M.M. Ahmed, and S.M. Gaweesh, *Assessment of the effectiveness of connected vehicle weather and work zone warnings in improving truck driver safety.* IATSS Research, 2020. **44**(3): p. 230-237.
30. Hsu, T.-P., K.-L. Wen, and C.-H. Liu, *Safety effect analysis of motorcycle V2I collision warning system.* IET Intelligent Transport Systems, 2021. **n/a**(n/a).
31. Farah, H., et al., *Evaluation of the effect of cooperative infrastructure-to-vehicle systems on driver behavior.* Transportation Research Part C: Emerging Technologies, 2012. **21**(1): p. 42-56.
32. Rahman, R., S. Hasan, and M.H. Zaki, *Towards reducing the number of crashes during hurricane evacuation: Assessing the potential safety impact of adaptive cruise control systems.* Transportation Research Part C: Emerging Technologies, 2021. **128**: p. 103188.

33. Rahman, R., et al., *Assessing the crash risks of evacuation: A matched case-control approach applied over data collected during Hurricane Irma.* Accident Analysis & Prevention, 2021. **159**: p. 106260.
34. Chang, Y. and P. Edara, *Evaluation of a reservation-based intersection control algorithm for hurricane evacuation with autonomous vehicles.* International Journal of Disaster Risk Reduction, 2018. **31**: p. 1152-1158.
35. Rizvi, S.R., et al. *A Novel Approach to Reduce Traffic Chaos in Emergency and Evacuation Scenarios*. in *2007 IEEE 66th Vehicular Technology Conference*. 2007.
36. Bian, R., et al., *Modeling Evacuees' Intended Responses to a Phased Hurricane Evacuation Order.* Applied Sciences, 2023. **13**(8): p. 5194.
37. FHWA. *Highway Statistics Series*. 2022 [cited 2023; Available from: https://www.fhwa.dot.gov/policyinformation/statistics/2021/dl22.cfm