# Effects of Auditory Alerts for Vehicle-to-Vehicle (V2V) Collision Warning Systems

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## Abstract

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Collision warning systems (CWSs) have shown great benefits in improving traffic safety by alerting drivers of potential collisions. However, some warning systems require information from nearby vehicles, which could be addressed uniquely by vehicle-to-vehicle (V2V) communications. Different alerting cues are needed given the type of threat, whether they can be obviously identified (lead vehicle slowing down) or more hidden in nature (intersection conflicts). However, a unified standard for designing and implementing the warning alert for these systems still does not exist. The goal of this dissertation is to examine the effectiveness of auditory collision warnings and identify their impacts on drivers' avoidance performance. Two driving simulator studies with different V2V scenarios were conducted. The objective of the first study was to examine the effects of acoustic forward collision warnings (FCWs) on drivers' avoidance behavior in a rear-end collision scenario (with an apparent threat). The findings showed that driving behavior, i.e. reaction time and response intensity differed given FCWs with different urgency levels. The objective of the second study was to identify

the effects of intersection movement assist (IMA) warning messages on drivers' avoidance behavior in a red-light-running (RLR) scenario (with a latent threat). The findings showed that drivers' avoidance performance and eye movements were significantly impacted by the presented warning information and training of the system. Combined data from two studies, partial least squares (PLS) path models were developed to reveal the causal relationships among warning conditions, drivers' avoidance behavior, and collision abatement. The models illustrated that the auditory warnings have both a direct and indirect effect on collision occurrence with the indirect effect playing a more critical role. Understanding the effects of warnings will help target the appropriate auditory characteristics and warning contents for different CWSs.

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# GLOSSARY

AEBS: Advanced Emergency Braking System

ADAS: Advanced Driving Assist System

AIS: Abbreviated Injury Scale

BRT: Brake Reaction Time

BSW: Blind Spot Warning

CI: Confidence Interval

CWIM: Crash Warning Interface Metrics

CWS: Collision Warning System

DNPW: Do Not Pass Warning

DOT: Department of Transportation

DSRC: Dedicated Short-range Radio Communication

EEBL: Emergency Electronic Brake Lights

FCWS: Forward Collision Warning System

ICF: Informed Consent Form

IMA: Intersection Moving Assist

ITS: Intelligent Transportation System

LDW: Lane Departure Warning

LTA: Left Turn Assist

LTAP/OD: left turn across pathopposite direction

NADS: National Advance Driving Simulator

NHTSA: National Highway Traffic Safety Administration

PCP: Perpendicular Crossing Paths

PLS: Partial Least Squares

RECAS: Rear-end Collision Avoidance System

RLR: Red-Light Running

RT: Reactiom Time

SEM: Structural equation modeling

TFF: Time to First Fixation

TRRT: Throttle Release Reaction Time

V2V: Vehicle-to-Vehicle

VMT: Vehicle Miles Traveled

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# DEDICATION

To all my beloved families, for their great support and unconditional love.

# Chapter 1

# BACKGROUND

This chapter provides an overview of Vehicle-to-Vehicle (V2V) communication and how V2V-based collision warning systems (CWSs) can be used for specific situations. Literature on modalities and characteristics of warning alerts are summarized. Measures used for evaluating the effectiveness of CWSs from previous studies are also discussed in this chapter. The objectives and aims of the dissertation are explained at the end of the chapter.

## *1.1 V2V-based Collision Warning Systems (CWS)*

### *1.1.1 Vehicle-to-Vehicle (V2V) Communication*

V2V communication is the wireless transmission of information between vehicles. V2V communication can prevent accidents by allowing vehicles sharing data with each other through an ad-hoc mesh network (Rouse, 2014). As an important component of intelligent transportation system (ITS), the U.S. Department of Transportation (DOT) and the National Highway Traffic Safety Administration (NHTSA) have been dedicated with academic institutions and automobile industry to advancing the lifesaving potential of this technology for decades.

V2V communication systems are composed of transmit devices, installed in vehicles, to exchange messages containing information about what they are doing through high-speed wireless network. The information includes vehicle's speed, location, heading direction, route and operational status (Li et al., 2018). Other vehicles in the network receive the messages in real time and send back similar data, establishing an information exchange process. By sharing real-time information among vehicles, V2V system can prejudge hazards in case the driver is unaware of and help the driver respond more timely to avoid the hazard.

The V2V safety applications require rapid message delivery and acquisition with high reliability, and the highest security and privacy standards. V2V system utilizes the dedicated short-range radio communication (DSRC) to exchange information to satisfy these particular requirements (Dey et al., 2016). Communicating though particular wireless signals, V2V system can offer omni-directional coverage, detect around corners and "see through" other vehicles. Using DSRC, V2V communication provides an operational range up to 300 meters, exceeding the capabilities of systems which use ultrasonic sensors, cameras, and radars. Thus, V2V system can detect hazards much earlier and allow more time for drivers to take actions.

### *1.1.2 Demand for Traffic Safety*

According to the national transportation statistics in 2016 (Spiegelman et al., 2016), the traffic fatalities in U.S. have declined consistently, the fatality rate per 100 million vehicle miles traveled (VMT) dropped from 3.35 in 1975 to 1.18 in 2016. This can be attributed to various safety technologies, education programs, the enforcement of law and standards, such as mandatory of seat belts, implementation of airbags, and prohibition of cellphone usage while driving. Although all these policies and "passive safety" systems will continue to help reduce fatalities and injuries, NHTSA (2013) believes the greatest benefits in traffic safety will come from broad-scale application of crash avoidance technologies, which may not only mitigate the severity of the crashes but avoid them entirely. In recent years, the U.S. DOT conducted a preliminary analysis of crashes that could be addressed by V2V technology (Najm et al., 2013). Among the total 37 identified pre-crash scenarios (Najm et al., 2007), 22 pre-crash scenarios can potentially be mitigated and even avoided using V2V technology. If all these crashes could be prevented, the V2V could potentially address approximately (Najm et al., 2013):

- 81% of all unimpaired light vehicle crashes
- 27,000 fatalities, 1,800,000 injuries and 7,3000,000 property damage crashes annually based on 2004 - 2008 crash data.

In 2014, NHTSA announced that it would begin to taking steps to enable V2V communication technology for light vehicles and released a supporting comprehensive research report (Harding et al., 2014). The report estimated that two V2V safety applications, Intersection Moving Assist (IMA) and Left Turn Assist (LTA) could prevent

- 41% to 55% of target intersection crashes
- 36% to 62% of left turn crashes

- 413,000 to 592,000 crashes annually
- 777 to 1,083 fatalities annually
- 191,000 to 270,000 Abbreviated Injury Scale (AIS) injuries annually

It is important to recognize that consumer acceptance would also impact the safety benefits of the technology. A recent study by Lukuc (2012) showed that more than 80% of drivers would like to have some advanced V2V safety warning systems (see Table 1.1), which indicates an immediate consumer demand for V2V warning systems.

Table 1.1: Driver Acceptance as a Function of Safety Feature (Lukuc, 2012)

| Features | Acceptance Ratio |
|---|---|
| FCW: Forward Collision Warning | 90.50% |
| IMA: Intersection Movement Assist | 95.50% |
| LTA: Left Turn Assist | 83.80% |
| BSW/LCW: Blind Spot/ Lane Change Warning | 90.90% |
| EEBL: Emergency Electronic Brake Lights | 91.40% |
| DNPW: Do Not Pass Warning | 88.60% |

### *1.1.3 Primary V2V-based CWSs*

In-vehicle collision warnings are designed to alert a driver of potential hazard or crashes around the vehicle. V2V communication extends and enhances current collision avoidance systems which use radars and cameras to identify collision threats. Based on crash data of light vehicles from 2004-2008, Najm et al. (2013) developed a list of prioritized pre-crash scenarios for V2V applications. The top six target pre-crash scenarios include rear-end, straight crossing, lane change, left turn across pathopposite direction (LTAP/OD), opposite direction and traffic control device violation (Figure 1.1).

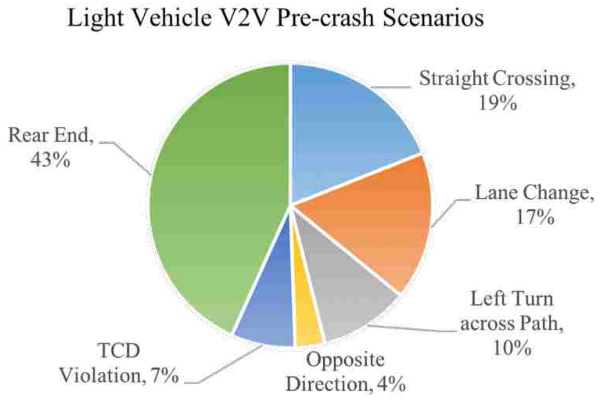


Figure 1.1: Percent of Total Crashes by Target Pre-crash Scenarios

- Forward Crash Warning (FCW)

Rear-end collisions, in which a vehicle collides with the rear of a slower moving or stopped preceding vehicle, are among the most common of vehicle-related accidents. In 2014, there were nearly 2 million police-reported rear-end collisions, which represents over 30% of all police-reported crashes (Cicchino, 2017). Each year, rear-end collisions kill approximately 17,000 people and injure over 500,000 people (Helsey, 2015). With the introduction of smart phones and new in-vehicle technologies, drivers today are more easily distracted in vehicles.

According to a National Highway Traffic Safety Administration report, up to 87 percent of rear-end crashes are related to driver distraction (NHTSA, 2007).

A Forward Collision Warnings System (FCWS) can detect vehicles and other obstacles in front of the vehicle. If an obstacle is detected and the collision risk exceeds a certain safety threshold, an alert is issued. FCWS can effectively draw a driver's attention to critical roadway incidents and has the potential to reduce both the severity and occurrence rate of rear-end collisions. Jermakian (2011) estimated that FCWS along with Autonomous Emergency Braking System (AEBS) can potentially prevent or mitigate up to 70% of rear-end collisions and 20% of all passenger vehicle collisions. The Highway Loss Data Institute, which performed a series of studies analyzing U.S. insurance claim rates, found that FCWS alone was associated with 7% - 22% reductions in rates of property damage liability claims and 4% - 25% reductions in rates of bodily injury liability claims.

However, the FCWS that uses radar or cameras cannot provide a timely warning for very high speed changes. V2V does have this capability with its longer coverage range and can get data directly from other vehicles, including data such as operational statues that cannot be collected by radars or cameras.

- Intersection Maneuver Assist (IMA) & Left Turn Assist (LTA)

Intersections can include many complex road segments that impact the road users ability to maneuver safely (Lombardi et al., 2017; Werneke and Vollrath, 2013; Bella and Silvestri, 2017). It requires large cognitive efforts for drivers to identify and process visual and spatial information while also maintaining appropriate control of their vehicle. Intersection-related crashes have accounted for more than 40% of all crashes and 20% of all fatal crashes in the US, second only to rear-end crashes (Cunard et al., 2004).

IMA and LTA were expected to significantly help reduce the number and severity of the target intersection-related collisions: crossing-path collisions. A crossing-path collision is defined as two road users involved in a collision while they are crossing travel paths. Perpendicular crossing paths (PCP) and left turn across path/opposite direction (LTAP/OD) are the most two common types of cross-path collisions (Najm et al., 2001).

A PCP collision is two vehicles traveling in perpendicular paths and colliding at an intersection. If equipped with IMA, the driver will receive warnings when it is not safe to enter an intersection. Figure 1.2 illustrates one of the most common scenarios that IMA can address. In this scenario, both drivers are unable to see another approaching the intersection and the stop sign is not working. Hence, the truck and the passenger vehicle are at risk of colliding. With IMA system, drivers can receive warnings which alert them to take actions to avoid the imminent collision.

Left Turn Assist (LTA) is designed to prevent LTAP/OD collisions. A LTAP/OD collision is a vehicle attempting a left turn collides with an oncoming vehicle traveling straight through an intersection. LTA will send warnings to the driver when he/she is attempting to turn left at the intersection while the oncoming traffic will make the turn unsafe.

In the report released by NHTSA (Harding et al., 2014), the effectiveness of IMA and LTA were estimated using a computer simulation mode called Safety Impact Methodology (SIM) combined with driving simulator (MiniSim) experiments. According to this report, IMA warning can help avoid 41% - 55% of PCP collisions and reduce the severity of PCP collisions by an average of 1.17 mph (14.3%) delta-V. LTA can prevent up to 62% of LTAP/OD crashes if all the users turn signal when turning.

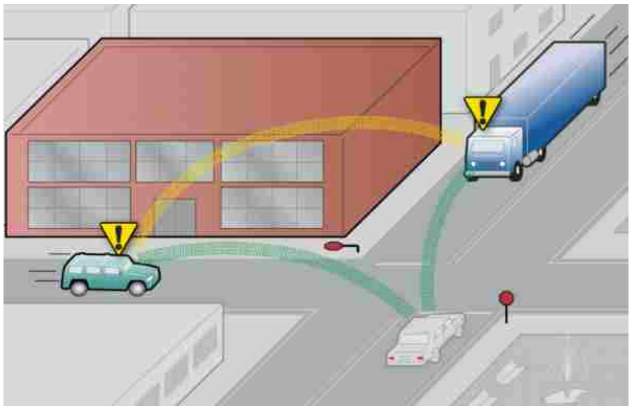


Figure 1.2: Example of A Common IMA Scenario (Harding et al., 2014)

- Blind Spot Warning (BSW) & Lane Change Warning (LCW)

Lane change collisions account for 17% of the V2V target collisions (Najm et al., 2007). BSW and LCW are designed to prevent this kind of collisions. These two systems send advisory warnings to the driver when another vehicle in an adjacent lane is or will be soon in the driver's "blind spot" zone.

- Emergency Electronic Brake Light (EEBL)

According to the V2V Communications Fact Sheet (2014), EBBL warns the driver to brake in a situation when another vehicle traveling in the same direction decelerates quickly but may not in the driver's line-of-sight. The EEBL warning allows the driver to "see through" other vehicles or bad weather conditions (i.e. fog or heavy rain) and detect the potential abrupt stop of traffic ahead.

## *1.2 Warning Alerts*

### *1.2.1 Warning Modalities*

There are three commonly used alert modalities for CWSs in passenger vehicles: auditory warnings, visual warnings, and tactile (or haptic) warnings. Visual warnings alert drivers by displaying warning information on the instrument cluster or in a heads-up display (Wege et al., 2013). However, when presented alone, visual warnings may go unnoticed by drivers whose attention is away from the location of the visual icon (Curry et al., 2009). Additionally, a visual warning may allocate a driver's attention toward visual icons rather than toward the roadway. Especially when several visual icons exist on the dashboard, it can increase the driver's workload and the likelihood of a crash (Baumann et al., 2004).

Tactile or haptic warnings provide vibration cues to drivers in a location where they have direct contact such as the seat, steering wheel or pedal. Some tactile warning systems can even allocate drivers' attention to a specific direction or position (Haas and Erp, 2014). However, drivers may also miss haptic or tactile warnings if the driver is not in direct contact with the specific portion of the vehicle when the alert is issued. The sensitivity of of tactile warnings can be impacted even by the layers and thickness of the driver's clothes (Verbunt and Bartneck, 2009).

Using representational sounds to alert of potential hazards, auditory warnings are widely used in modern vehicles. Auditory warnings provide alerts to the drivers using omni bearing sound signals to ensure that drivers receive the warning regardless of where he or she is looking (McCallum, 2006). Some auditory warnings even provide additional information about the threat (Haas and Edworthy, 2006). Moreover, the auditory warning is also more applicable than other forms of warnings, because it can be easily embedded into navigation system or similar audio systems that are prevalent in modern vehicles (Regan et al., 2006).

### *1.2.2 Characteristics of Auditory Warnings*

#### *Acoustic Characteristics of Monotonous Warning*

Acoustic characteristics of warnings fall in to three categories: base sound, pulses and burst (Figure 1.3). Characteristics such as fundamental frequency and harmonic series create an identifiable base sound. The base sound can be arranged into pulses with characteristics such as inter-pulse interval (silence between pulses of sound) and amplitude envelopes. Pulses can be further arranged into one or more bursts of sound with characteristics like inter-burst interval(intervals of silence between the bursts). Different alerting sounds can be generated by manipulating these characteristics.

An effective auditory alert for CWSs should be noticeable, catch the driver's attention, depict significant urgency, and deliver the correct information to drivers. Previous studies noted that drivers respond faster to alerts that sound more urgent within an acceptable range (Burt et al., 1995; Haas and Casali, 1995; Edworthy et al., 2000). The urgency of measures can be manipulated by changing the physical characteristics (e.g.,frequency, inter-pulse interval) of an auditory alert. Many researchers made efforts in showing how different characteristics of auditory alerts are associated with different perceived urgency levels. For example, alert tones with higher fundamental frequency, shorter inter-pulse, and higher intensity (loudness) are perceived as more urgent (Hellier et al., 1993; Haas and Casali, 1995; Marshall et al., 2007). As part of the Crash Warning Interface Metrics (CWIM) program, Lerner et al. (2015) conducted a series of experiments to identify the ranges of auditory characteristics where sounds would be classified by drivers as highly urgent collision alerts and provide mean value for each individual characteristic of those highly urgent alerts: base frequency (931.71 Hz), Tempo or inter-burst interval (330 ms), pulse duration (460 ms), and pulses per burst (2.73).

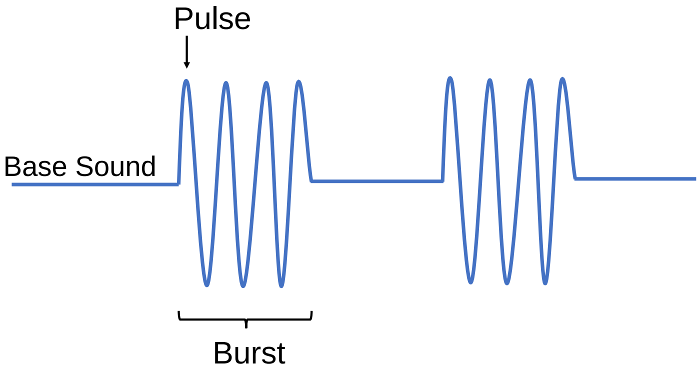


Figure 1.3: Decomposition of A Sound

### *Verbal Messages of Speech-based Warnings*

The auditory warning can be further divided into two types: non-speech and speech-based alerts. Non-speech alerts are monotonous and repetitive sounds, such as “bi-bi” beep sound, while speech-based message is delivered by synthesized voice that imitates human voice, such as “attention” or “watch your left-hand side” (Chang et al., 2009). Non-speech information are recommended for attentional warnings such as for distracted drivers in rear-end collision scenarios (Mohebbi et al., 2009; Spence and Ho, 2008).

Speech-based warnings have the advantage of conveying the urgency of the situation through semantics rather than acoustics. This has made speech-based warnings of great interest for many researchers to consider for collision avoidance systems. As early as 1996, Edworthy and Adams indicated that synthesized voices can provide time-critical information aimed at avoiding impending disaster in a calm, monotone voice. In contrast, the non-speech warning in high-pitched, high-rate tones is likely to startle the listener. Compared to understanding a verbal command, the mental processing requirements might be higher in understanding the meaning of a tone-based warning under an intersection approach context. Lee et al. (2007) showed that the verbal STOP command was more effective in prompting a stopping behavior at intersections when compared to a tonal warning. Chang et al. (2008) considered speech-based messages for intersections collision warning systems (ICWSs) and showed that they could lead to a significant reduction in drivers’ perception-reaction time (the reaction time to release accelerator) at an intersection. They found that when drivers were unaware of the direction of an oncoming vehicle, a speech message was of greater assistance than a beep sound. Comparing different speech warning massages, Baldwin and Moore (2002) found that the signal word Danger was perceived as more semantically urgent compared to the words Warning and Caution, which in turn were perceived as more urgent compared to Notice.

## *1.3 Effectiveness of CWS*

### *1.3.1 Performance Measures*

#### *Collision Involvement and Collision Severity*

Collision involvement is the most intuitive measure to evaluate the avoidance effectiveness of CWSs. Suetomi et al. (1995) found that the collision rate was reduced from 18.6% to 2.3% with a warning system provided, when following a decelerating lead vehicle. Lee et al. (2002) examined that the rear-end collision avoidance systems (RECASs) can redirect the driver's attention to the road and therefore reduced the collision by 50-80% using a high-fidelity driving simulator. In another simulator study conducted by Brown et al. (2001), RECASs can lead to nearly 85% collision reduction using a kinematics-based algorithm. Chang et al. (2009) and Xiang et al. (2016) investigated the effectiveness of CWs in red-light running (RLR) scenarios and found the collision rate was considerably reduced even with late warning condition. In addition to collision avoidance, the mitigation in collision severity is one of the most important measures to estimate the effectiveness of CWSs. The severity of collision was always measured by the collision velocity (or delta velocity) in simulation study. In the study conducted by Lee et al. (2002), the collision velocity was reduced by 87.5 - 96.5%

using RECASs. And the collision velocity reduction of RECASs was also over 80% according to the experiment conducted by Brown et al. (2001). Based on the NHTSA's report (Harding et al., 2014), the IMA warning can lead to a 22.7% collision velocity reduction in the PCP scenario.

### *Avoidance Behavior*

Drivers' reaction time is one of the most important measurement components in collision warning research (McGehee et al., 2000). It plays a crucial role in collision avoidance success and it is believed a quicker reaction time is better for avoiding a collision. Reaction time is defined from the period when the alert is issued to the moment when the driver begins to take an action. It may include measures for a series of actions conducted by drivers i.e. reaction time of accelerator release, braking, steering or accelerator depressing. More complex responses would take longer. For example, braking requires lifting the foot from the accelerator, moving laterally to the brake pedal and then depressing, which is far more complex than just releasing the accelerator or turning the steering wheel. Previous studies have proved that a quicker reaction time can reduce the probability and severity of crashes, which was often used as a primary parameter to evaluate the effectiveness of CWSs (Uno and Hiramatsu, 2001; Chang et al., 2009; Xiang et al., 2016). Since the vast majority of drivers chose to brake rather than swerve or accelerate to avoid an imminent collision, brake reaction time (BRT) has been investigated in many CWS studies using various research paradigms and instrumentation (Gray, 2011; Ruscio et al., 2015; Yan et al., 2014; Xiang et al., 2016). Lee et al. (2002) decomposed driver's response progress and examined the time from lead vehicle braking to initial accelerator release, the time from accelerator release to initial brake depress, and the time from initial brake press to maximum deceleration. In addition to the reaction time of initial accelerator release and the reaction time of max brake reaction, McGehee et al. (2000) also examined the reaction time of initial steering using both simulator and test track data.

Reaction intensity represents the variables measuring how intense a driver responds to warnings. For a response of braking,the measures can include mean/max deceleration rate and speed reduction etc. Previous studies have shown that the severity of crash is determined by the crash velocity (Elvik, 2013). Larger declaration rate or speed reduction would help reduce the severity of crash by reducing the vehicle speed (even to stop). In an experimental study examining the effects of ICW system (Sternlund et al., 2017), the speed reduction and deceleration rate were examined for auditory and visual warnings. The speed was reduced in all scenarios, and the deceleration differed given different scenarios. But no difference was detected in deceleration rate between visual and auditory ICWs. Zhang et al. (2015) examined the the effects of direction and non-directional auditory warnings and found that the mean deceleration in the case of a directional warning was smaller than that in the case of a non-directional warning. In another study conducted by Xiang et al. (2016), it was found that the mean deceleration with warning presented was significantly larger than that in no warning condition. However, there is no significant difference in the mean deceleration between late and early warning conditions.

### *1.3.2 Impacting Factors*

#### *Age*

The effectiveness of CW can be greatly impacted by age, especially to older drivers. This is primarily associated with degradations in cognition, vision, and other physical conditions (Anstey et al., 2005). Older drivers were also shown significant degradation of maintaining speed under cognitive secondary workload compared to other drivers (Son et al., 2010; Reimer et al., 2011). As a result, they tend to fail with severe sequences under the situations with great momentary mental workflow (Harms, 1991; Hakamies-Blomqvist et al., 1999). Some researches showed that CWS benefits older drivers most by providing useful assistance to compensate their limitation in motion perception, peripheral vision, selective attention, and speed maintenance (Mitchell and Suen, 1997; Shaheen and Niemeier, 2001). It is also found older drivers indicated a higher acceptance to CWSs (Oxley and Mitchell, 1995).

#### *Gender*

Gender is another important factor in driving behavior and thus could affect the effectiveness of CWS as well. For example, Turner and McClure (2003) found gender is significantly associated with drivers' aggression and high-risk acceptance. Women are found generally have lower levels of confidence in their driving skills compared to men (D'Ambrosio et al., 2008). Son et al. (2011) found female driver groups has the lowest acceptance of ADAS and they are affected by FCW significantly and towards more dangerous conditions.

### *Driving Experience*

Drivers with better driving skills and more driving experience are able to respond to emergencies more effectively. Compared with novice drivers, experienced drivers had greater speed reduction and shorter reaction time (Mueller and Trick, 2012). In addition, experienced drivers had more complete inspections of the roadway and better perceptions of potential hazards than novice drivers (Underwood et al., 2002; Deery, 1999).

### *Training*

Users' familiarization of the system can impact the effectiveness of CWSs. Koustanai et al. (2010; 2012) conducted a series of studies that showed that familiarization led to better understandings of the FCW, thus making driver/system interactions more effective and safer. However, there is limited studies that relate the driver's understanding of CWS and their driving behavior. System training can also vary greatly in simulator studies. Participants may not be trained before the test session (Graham, 1999), or the training given was not documented (Abe and Richardson, 2006). In some studies, a written use-oriented presentation or a use-oriented video was provided to participants prior to the formal test (Cahour and Forzy, 2009; Balk, 2014).

## 1.4 Gaps in Literature

Numerous studies examining the potential benefit of in-vehicle safety systems have typically compared the safety benefits between different alert modalities rather than between different levels of a single alert characteristic within a single modality (Haas and Edworthy, 2006; McCallum, 2006; Lee et al., 2006). Previous studies showed that an acoustic characteristic at high urgency levels could accurately convey meaning for urgent situations (Baldwin and Lewis, 2014; Edworthy et al., 1991). However, auditory alerts with too high a level of perceived urgency may startle or produce other negative effects on drivers' responses (Blumenthal, 1996). Moreover, highly urgent alerts may increase annoyance and workload (Wiese and Lee, 2004). Thus, it is important to identify the range of each single auditory characteristic that would span the transition point between effective alerts and ineffective alerts (Lee et al., 2006).

Many studies have been conducted on the developments of CWSs which address apparent threats such as FCWS (Lee et al., 2002; Spence and Ho, 2008; Mohebbi et al., 2009). Drivers can easily identify the hazard when their attention is brought back to the roadway. However, the research scope of a more advanced V2V CWSs, i.e. IMA is still limited, and drivers' behavior in scenarios with hidden hazards need to be further investigated. Although speech or verbal message might be a more promising way to deliver warning information to drivers in scenarios where hazards cannot be easily detected (Spence and Ho, 2008; Porter et al., 2008), the effects of different information presented by warnings remain unknown. It's of crucial importance to identify the warning information or content that can best assist the driver in detecting hazards and avoiding the collision.

Previous studies examined the influences of CWSs based on limited performance measures (i.e., reaction times and collision occurrence). The detailed characteristics of avoidance behavior given different types of scenarios still need be understood comprehensively. Particularly, few studies were found investigating the causal relationships between warnings, collision avoidance behavior, and collision abatement.

## *1.5 Study Objectives and Specific Aims*

The overall objective is to examine the effectiveness of different auditory warnings and understand how these warnings affect drivers' avoidance behavior in multi-vehicle pre-collision scenarios. The pre-collision scenarios include rear-end collision and straight crossing collision at intersection with corresponding V2V applications FCW and IMA. This study will try to solve the following four research questions with four specific aims.

**Research Question 1:** Will the monotonous auditory warnings be effective in a collision scenario with an apparent threat, i.e., leading vehicle decelerating? More importantly, how does the acoustic characteristic of the warning (i.e., FCW) impact drivers' collision avoidance performance in this scenario?

***Aim 1:*** *Examine the effectiveness of monotonous auditory FCW in the rear-end collision scenario. Investigate the effects of acoustic characteristics of FCW on drivers' avoidance performance.* A driving simulator study with 192 participants across the U.S was designed and conducted with a pre-collision scenario that included a lead vehicle decelerating. The acoustic characteristics, fundamental frequency, and duty cycle, were examined at three urgency levels. Drivers' collision avoidance behavior was measured using two reaction times (throttle release, brake) and three response intensities (maximum brake pedal force, maximum lane deviation and response type). Collision occurrence and drivers' collision avoidance behavior were examined and compared given different warnings.

**Research Question 2:** In a collision scenario with latent threats, will the non-speech and speech warnings be effective to help drivers avoid a collision? Also, how does different information presented by the warning affect drivers' behavior?

***Aim 2:*** *Examine the effectiveness of non-speech and speech-based IMA warnings in a scenario with latent threats. Investigate the impacts of different warning information on drivers' avoidance performance.* A driving simulator study with 80 participants was designed and conducted with a red light running (RLR) scenario. One monotonous and three speech-based IMA warning messages containing different information were tested. Drivers' collision avoidance behaviors were examined through reaction time, two eye movement measures (fixation pattern and time to first fixation) and three avoidance response measures (response type, maximum deceleration/acceleration, and speed change).

**Research Question 3:** In collision scenarios with apparent and latent threats, what is the relationship between warnings, drivers' avoidance behavior, and collision occurrence?

***Aim 3:*** *For FCW and IMA scenarios, investigate the causal relationship among warnings, drivers' avoidance behavior, and collision abatement.* Based on the data from two simulator studies, two separate models with different structures were proposed to examine the causal relationship among warnings, drivers' behavior and collision occurrence. The performance of different warnings was compared based on the model results.

**Research Question 4:** How drivers' subjective rating of warnings would align with their avoidance behavior?

***Aim 4:*** *Examine drivers' subjective ratings of FCWs and IMA warnings. Investigate correlations between drivers' subjective ratings and their avoidance behavior.* Based on the questionnaire data from two studies, a correlation study was proposed to examine the relationship between drivers' perceptions of presented warnings and their actual avoidance performance including collision involvement, reaction time and other avoidance behavior measures.

## *1.6 Chapter Summary*

This chapter provided an overview of the current state of V2V-based CWSs, characteristics of auditory collision warnings, and measures of CWS effectiveness. Although the traditional CWSs have shown great benefits and advantages in mitigating the number and severity of collisions, the efficacy of auditory warnings in different V2V target pre-collision scenarios needs to be further examined. Particularly, the impacts of warnings on drivers' avoidance behavior need to be comprehensively understood. The study objectives with research aims were provided. In the next two chapters, the two simulator studies are presented. Chapter 4 combines the data from the two simulator studies for partial least squares (PLS) path models. Chapter 5 describes the subjective ratings and the last Chapter discusses some of the more interesting findings, study limitations, and future work.

# Chapter 2

# STUDY ONE:
# SCENARIO WITH APPARENT THREATS (FCW)

This chapter presents Study 1, which examined the impacts of acoustic characteristics on the effectiveness of FCW in a scenario with an apparent threat (leading vehicle decelerating). The data analyses in this study were based on a driving simulator study with 192 drivers, where two acoustic characteristic were each manipulated cross three levels.

## *2.1 Objective*

The objective of this study is to examine the effectiveness of monotonous FCWs for distracted drivers and understand how drivers' avoidance performance is affected by acoustic characteristics of the FCWs.

## *2.2 Methodology*

### *2.2.1 Participants*

The data were collected at four different sites: Iowa City, IA, Seattle, WA, Clemson, SC, and Austin, TX. The combination of these sites provides geographic variety that includes bi-coastal, southern, and mid-west regions of the United States, a range of population densities and socioeconomic factors from which to draw a representative sample.

192 men and women, aged 25-55 years old, successfully completed the study. They had no known health issues based on a pre-screening tool. The age and gender groups are comparable to previous related studies. For example, the CWIM project used a similar age group of 25-59 to investigate people's comprehension of message content for visual status displays of advanced CWSs (Lerner et al., 2011). They were required to have a valid US driver's license for at least two years and drive at least 3500 miles/year. All the participants need to have experience engaging in distracting activities while driving, such as talking on a cellphone, sending or receiving text messages or eating. All the enrolled drivers should not had any participation in simulator study in the past six months. All these participants were recruited through advertisements and flyers. All the participants were divided into two age groups, 25-40 and 41-55 years of age with equal number of males and females.

### *2.2.2 Apparatus*

All data collection sites used National Advanced Driving Simulator (NADS) 1/4 cab miniSims with 42″ 720p plasma displays. The simulator includes three screens (3.0′ [wide] by 1.7′ [tall] each) positioned four feet away from the driver's eye point.

### *2.2.3 FCW Alerts*

The fundamental frequency is the lowest of all the frequencies present in a tone and used to determine base sound. It is a characteristic used widely to investigate perceived urgency and can be easily manipulated (Hellier et al., 1993; Maccarini et al., 2017). Duty Cycle is the fraction of active pulse duration and commonly expressed as a percentage or a ratio. It specifically describes the fraction of time a sound is on (the pulse is active) over an interval or period of time. Lower duty cycle makes sound sharper and thinner. The range of fundamental frequency and duty cycle used in past studies include 150Hz to 680 Hz and 0.1 to 0.9, with the higher fundamental frequencies and higher duty cycles being associated with higher perceived urgency. Initial pilot studies show that these two alert characteristics can be quantified across three levels: low, medium and high (see Table 2.1) . When adjusting the level of one characteristic, the other one was held constant at the medium level.

Table 2.1: FCW Alerts

| Alert | Acoustic Characteristics | |
|---|---|---|
| | Fundamental Frequency | Duty Cycle |
| Duty cycle & Fundamental frequency: Medium (D,F-M) | 319 | 0.5 |
| Duty cycle: low (D-L) | 319 | 0.25 |
| Duty cycle: high (D-H) | 319 | 0.75 |
| Fundamental frequency: low (F-L) | 234 | 0.5 |
| Fundamental frequency: high (F-H) | 641 | 0.5 |

As part of the experimental setup, sound settings are calibrated on each miniSim to match specifications. The specifications were designed to present the alerts at 75 dB with the ambient noise less than 60 dB, or 15 dB above maximum ambient noise levels. The ambient noise level included the engine sounds produced by the simulator. Each alert was about 3.5 seconds in duration and contained 3 bursts of 4 fast beeps (4 pulse/second). The inter-burst interval is 250 ms. An onset and offset time of 8 ms was used in creating each of the alert sounds. The amplitude waveform of the tone with medium duty cycle and fundamental frequency (D,F-M) is shown in Figure 2.1. To ensure consistency in each tested alert, researchers conducted daily sound calibration using sound pressure meters at the beginning of each experiment day and again after any significant breaks in data collection.

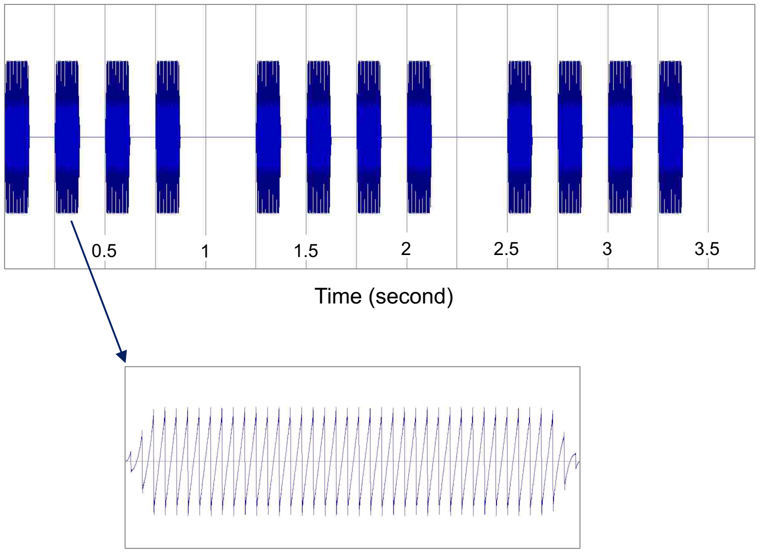


Figure 2.1: Wave form of D,F-M alert

### *2.2.4 Scenario*

This study employed a pre-crash situation of a potential collision between the host vehicle and a decelerating lead vehicle. The scenario involved the host vehicle going straight and following a lead vehicle in the same lane and path. The posted speed was 55 mph. While drivers can select their own driving speed (45 mph to 65 mph), the lead vehicle was programmed to change their speed such that it always maintain a headway of 2.2 seconds. Auditory instructions were given to the participants if their speed exceeded 65 mph or was below 45 mph. A distraction task is employed and presented five times during the drive. The first four instances of the task, one prior to beginning the drive and three during the drive, allowed participants to become familiar with the task prior to the final instance. During the last distracting task, while the participant was looking away from the forward view, the lead vehicle decelerated at 0.7 g to a stop as if it intended to make a left turn and a distinctive, non-speech auditory warning was presented from three speakers located under the simulator displays. The scenario took place on straight and level roads,in daylight with clear weather conditions. The screen-shot of the scenario and the time-line of the pre-collision event are shown in Figure 2.2.

### *2.2.5 Distraction Task*

During the 10 to 15 minutes of driving, participants needed to engage in a number of recall tasks. Five random single digit numbers were displayed for 472 ms each on a small screen located between 90 and 110 degrees to the right of the participant's forward-facing position. The total task duration was 2.36 seconds. The participant needed to repeat the numbers aloud after all five have been displayed in the correct order. These tasks have been shown to be effective in providing sufficient time for the rear-end collision events to unfold without the

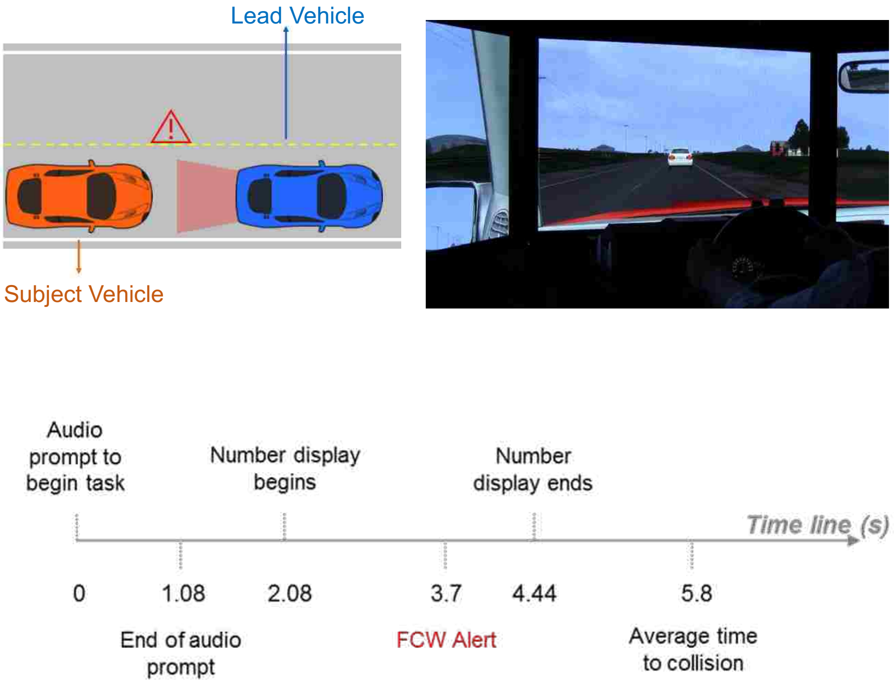


Figure 2.2: Lead Vehicle Decelerating Scenario and Event Time-line

participant looking forward too early (Lerner et al., 2015). Figure 2.3 shows a participant engaging in the distraction task.

### *2.2.6 Procedures*

This is a between–subject experimental design in that each participant was presented with only one test drive (one event) and one FCW warning condition. A between–subject design is used to capture the participant's most natural response, without any expectations of pre-crash scenarios. Before the test drive, participants completed an Informed Consent Form (ICF) and a questionnaire that covered some general questions about their demographics and driving experience. Each participant then received an overview of the simulator and

Figure 2.3: Number Recall Task

a description of the distraction task. There was no training on the CWSs or alerts, and participants were not told that there would be a situation with an imminent collision. This was purposely done to capture participants' natural response to the alert. Drivers who looked back to the front view early in the last distraction task (before the task was complete) were excluded from the data analysis (based on visually checking from experimenters).

After the test drive, each participant completed a questionnaire that asked them to rate the alerts they just heard. All the participants also had to complete a wellness questionnaire and a realism questionnaire. Drivers who reported moderate or more sever sickness or discomfort need to be withdrawn from the study. Drivers who rated the system unrealistic were also excluded from the data analysis. After all simulator procedures were completed, a debriefing statement was provided that explained the purpose of the research.

### *2.2.7 Response Variables*

Driving behaviors generally refer to drivers' responsiveness and skills at controlling the vehicle, such as ability to maintain vehicle speed, control lane deviations and their response to critical situation and potential hazards. The effectiveness of CWS was examined from the aspects of collision occurrence and collision avoidance behavior, which was based on reaction time and response intensity.

- Collision
  - Collision Occurrence(Yes/No): for each participant, whether he/she avoided the rear-end collision.
  - Collision Velocity: the severity of collision is strongly associated with the collision velocity (Richards et al., 2009; Jurewicz et al., 2016). Severity of collision decreases with reduced collision speed (Kloeden et al., 2001, 2002; Elvik, 2013). Given that two vehicles are involved in this scenario, the collision velocity is defined as the relative velocity (difference) between participant vehicle and lead vehicle.
- Reaction time (RT) has important implications for crashes. Quicker reaction time has been associated with a reduction of probability and severity of crashes (Chang et al., 2009). For this study, two variables related to brake response reflect how fast drivers take actions to avoid collision after an alert is issued.
  - Throttle Release Reaction Time (TRRT): defined by the time between the warning

  alert was triggered and the time that the host driver released the throttle pedal.
  - Brake Reaction Time (BRT): defined by the time between the warning alert was triggered and the time that the host driver treads the brake pedal.

- Response intensity (RespIntensity) represents how intensely the driver responds to the alerts. There are three variables that measure response intensity.
  - Maximum Deceleration (MaxDecel): defined by the maximum deceleration during the collision avoidance process (from the time that the driver begins to press the brake pedal to the time that collision occurred or the driver passed the conflict point)
  - Maximum lane deviation (MaxLD): defined by the deviation between the original position when the alert was issued and the maximum position away from the centerline during the driver's avoidance response.
  - Response Type (ResType): defined by the response type applied during the avoidance process (braking only/combination of braking and steering). To distinguish these intentional, imminent collision avoidance responses from unintentional driving behavior i.e. adjusting steering or speed, some criteria were applied to identify response. A braking response was noted if the maximum deceleration was larger than 0.1g after the warning was issued. A steering response was noted based on the steering angle and steering rate after the warning was issued. The steering angle deviation threshold was over 5 degrees and steering rate was over 10 de-

gree/s. These two conditions needed to be satisfied more than 50% of the time from alert to the end of the event.

## *2.3 Results*

Among the 210 participants recruited for this study, 192 successfully completed the test drive and their data were valid for further analysis. Of the 18 that were removed, 13 (6.2%) were removed from further analysis due to an invalid response for last distraction task (i.e., looked back too early or could not maintain control of the vehicle while engaged in a distraction task). Three of the 18 drivers (1.4%) were replaced due to moderate or more severe motion sickness. And two of the 19 drivers' data (0.9%) were excluded because they reported that the scenario was very unrealistic.

### *2.3.1 Collision*

#### *Collision Occurrence*

The collision rate is defined as the proportion of drivers who were involved in a collision during the rear-end crash event. Among the 192 completed tests, 140 collisions occurred, with the remaining 52 having successfully avoided the collision. The calculated collision rate for each warning condition is shown in Table 2.2. Providing warning alerts reduced the crash rate by up to 50% compared to the condition without the warning alert. For fundamental frequency, the alert with high level setting had the highest collision rate. While for duty cycle, the alert with high urgency level was associated with lowest collision rate.

Table 2.2: Collision Rate ($n = 32$ for each warning condition)

| Warning Alert | Collision Occurrence | Collision Rate |
|---|---|---|
| None | 30 | 30/32=0.938 |
| Duty cycle, Fundamental frequency - Medium | 24 | 0.781 |
| Fundamental frequency - High | 23 | 0.750 |
| Duty cycle - Low | 22 | 0.688 |
| Duty cycle - High | 20 | 0.625 |
| Fundamental frequency - Low | 19 | 0.594 |

A logistic regression model with a binary dependent variable (yes/no) for collision involvement was developed to investigate the impacts of different warning alerts on collision involvement (Table 2.3). Age group, gender, and warning condition were used as independent variables in the model. In addition, given that the speed among participants varied from 45 to 65 mph, the time to collision when the alert was issued (TTCatAlert) ranged from 1.66 to 2.77 s was also included as a covariate. The results show that age group, TTCatAlert and warning conditions significantly impacted the occurrence of a collision. Younger drivers (25-40 years old) tend to have a higher likelihood of a collision than drivers over 40 years old. Younger drivers also had a lower TTCatAlert, which may increase collision likelihood. Collisions are less likely to occur when a warning alert was present when compared to no warning present. This result is in line with previous studies (Cicchino, 2017; Lee et al., 2002). Among the different warning alerts, F-L alert and D-H alert are associated with lower collision occurrence than the other alert tones. The odds of having a collision can be reduced by up to 90% using these two alert settings compared to the condition without warnings.

Table 2.3: Logit Regression: Collision Involvement Model Results

| | Estimate | Std. Error | z value | P-value |
|---|---|---|---|---|
| (Intercept) | 9.387 | 4.233 | 2.218 | 0.026 |
| TTCatAlert | -5.220 | 2.642 | -1.976 | 0.048 |
| Alert: (Baseline:No Warning Alert) | | | | |
| Duty cycle, Fundamental frequency - Medium | -1.490 | 0.860 | -1.731 | 0.083 |
| Fundamental frequency - High | -1.490 | 0.863 | -1.727 | 0.084 |
| Duty cycle - Low | -1.851 | 0.846 | -2.188 | 0.029 |
| Duty cycle - High | -2.127 | 0.838 | -2.540 | 0.011 |
| Fundamental frequency - Low | -2.324 | 0.837 | -2.778 | 0.005 |
| Age: (Baseline: Female) | | | | |
| Male | 0.463 | 0.360 | 1.287 | 0.198 |
| Age: (Baseline: Older drivers 41-55) | | | | |
| Younger drivers (25-40) | 1.041 | 0.367 | 2.839 | 0.005 |

### *Collision Velocity*

Collision velocity has been shown to be strongly associated with collision severity. cCollision velocities were extracted from the drivers who crashed in the test drive. At the moment when the collision occurred, the participants' driving speed ranged from 22.21 to 52.99 mph and the lead vehicle speed was around 20 mph. Hence, the range of collision velocity varies from 2.19 to 32.97 mph. Analyses of variance (ANOVA) showed that the collision velocity significantly differed given the warning conditions ($F(5, 135) = 5.827, p < 0.001$). Compared to the no FCW condition, drivers' collision velocities were considerably reduced if they experienced FCW alerts (see Figure 2.4). The Tukey's HSD (honestly significant difference) test showed that collision velocity can be significantly reduced by as much as 8.6 mph with D,F-M alert presented ($p < 0.001$).

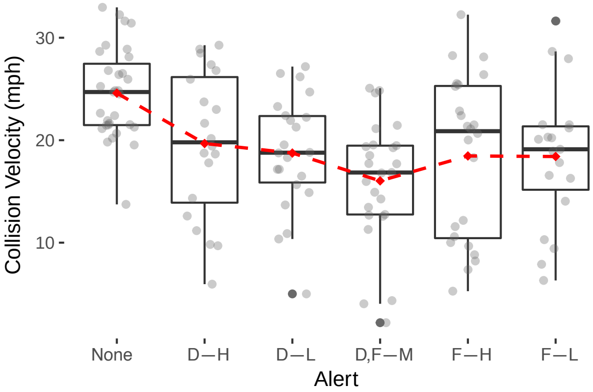


Figure 2.4: Collision Velocity (relative velocity) across FCW conditions

### *2.3.2 Avoidance Behavior*

#### *Reaction Time*

Participants in the imminent rear-end collision had one of four types of responses: no action, braking, steering, or a combination of braking and steering. Out of the 192 participants who completed all experimental procedures, 182 used braking, which is the primary response for avoiding a rear-end collision. Among those that braked, 96 also steered.

ANOVA results showed that both TRRT ($F(5, 180) = 11.072, p < 0.001$) and BRT ($F(5, 180) = 23.456, p < 0.001$) significantly differed between warning and no warning conditions. This suggested that audio warning alerts, in general, can effectively reduce these two reaction times and allow drivers more time to avoid a collision with the leading vehicle. As shown in Figure 2.5, drivers who were given F-H alert and D-L alert had slightly longer TRRT and BRT than the other warning tones. However, based on Tukey's Honest Significant Difference (HSD) test, the differences in TRRT and BRT among presented FCW conditions were not statistically significant.

Drivers' age group also had a significant impact on the reaction time to release the throttle pedal ($F(5, 180) = 3.573, p < 0.05$), with older drivers releasing the throttle pedal quicker on average than less experienced younger drivers, despite having similar BRT.

### *Response Intensity*

Because of the heterogeneous variances, a robust ANOVA using the Welch - James' statistic proposed by Johansen (1980) was conducted for the MaxDecel. The results showed that warning conditions have a significant impact on MaxDecel ($\chi^2 = 15.71, df = 5, p = 0.016$). Compared to the no warning group, the MaxDecel from drivers that experienced warnings were significantly larger. Figure 2.6 shows that most participants pressed the brake pedal hard when there is warning, generating a maxmimum deceleration of 0.8g. In the no warning

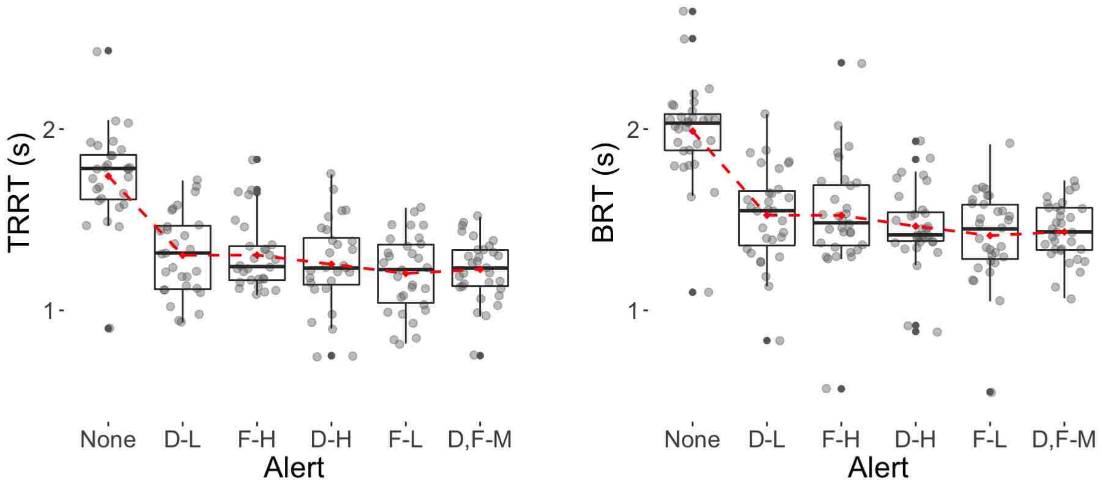


Figure 2.5: TRRT and BRT across FCWs

condition, there was much greater variation in MaxDecel with less hard braking.

The maximum lane deviation (MaxLD) from the lane centerline during the avoidance process was selected to measure the intensity level of the drivers' steering response. This is reasonable given that over 50% of the participants used both braking and steering as their avoidance response. The values of MaxLD ranged from 0.19 to 10.66 ft. Given that the lane width of the scenario is 9.8 ft., the host vehicle (half of the car) is considered out of its lane if the value of MaxLD is greater than 4.9 ft. A multivariate linear model was developed to investigate MaxLD across different warning conditions (Table 2.4). The results showed the effects of warning conditions on MaxLD are insignificant, indicating the observed effects of these tested warning alerts cannot be detected through this experiment. However, drivers' age group ($p = 0.03$) and the time to collision at alert ($p = 0.01$) do have significant impacts on the MaxLD with older drivers and a longer TTCatAlert tending to have greater MaxLDs.

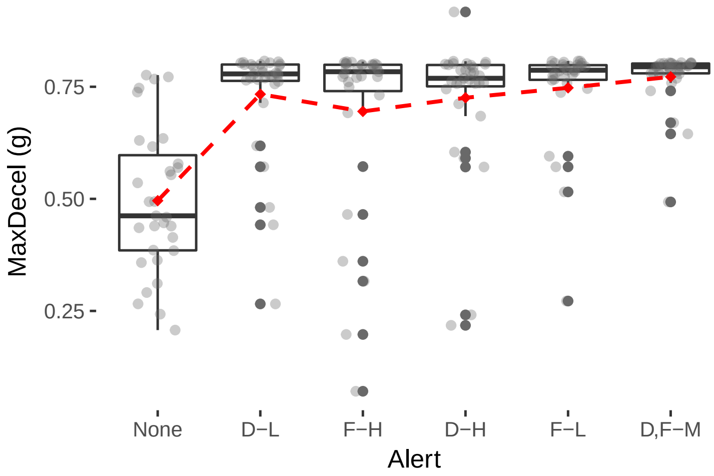


Figure 2.6: Distribution of MaxDecel across FCWs

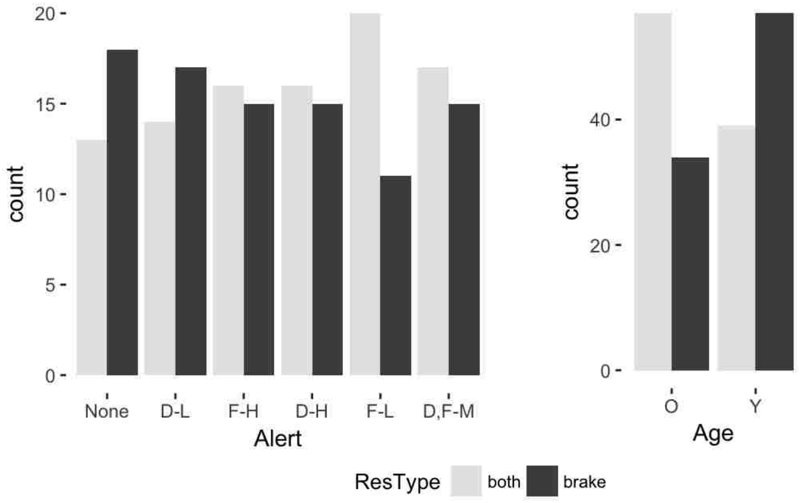


Figure 2.7: Response Type across FCWs

In this study, 92% of drivers either braked or both braked and swerved in the collision scenario. It is assumed that the combination of braking and swerving is a more complex response and reflects higher response intensity. Drivers who both braked and swerved had a lower collision rate (60.2%) compared with those who only braked (89%). Therefore, drivers' response type (ResType) was also included as an indicator for response intensity. Based on Figure 2.7, more drivers took a more complex response both braking and steering when warning alerts were provided especially when the F-L alert was presented. Also, older drivers with more driving experience were more inclined to avoid the collision through a combined response.

Table 2.4: Multivariate Model for MaxLD

| Independent Variable | Estimate | Std. Error | P-value |
|---|---|---|---|
| Gender ( Baseline:Female) | | | |
| Male | -0.510 | 0.292 | 0.082 |
| Age (Baseline: Older (40-55) | | | |
| Young (25-39) | -0.642 | 0.292 | 0.029 |
| Alert (Baseline: None) | | | |
| Duty cycle, Fundamental frequency - Medium | 0.105 | 0.507 | 0.837 |
| Fundamental frequency - Low | 0.026 | 0.506 | 0.959 |
| Duty cycle - Low | -0.454 | 0.506 | 0.371 |
| Duty cycle - High | 0.219 | 0.506 | 0.665 |
| Fundamental frequency - High | -0.299 | 0.506 | 0.556 |
| TTCatAlert | 2.482 | 0.980 | 0.012 |

### *2.3.3 Correlations among Performance Measures*

Drivers' avoidance process is a very complicated sequence that is composed of interacted responses. Figure 2.8 displayed the correlations between each pair of the performance measure. The results indicated that correlations exists among drivers' response behavior. Drivers' reaction times to release throttle and brake press were strongly correlated. The Pearson's correlation coefficient (PCC) is 0.73 ($p < 0.001$). Quicker throttle release was associated with quicker brake press. Moreover, drivers' reaction time were also negatively correlated with their MaxDecel and MaxLD, indicating shorter reaction time was associated with stronger response intensity (larger MaxDcel and MaxLD). The PCCs between BRT with MaxDecel and MaxDL are respectively -0.29 ($p < 0.001$) and -0.15 ($p < 0.04$). These two magnitudes of drivers' avoidance behavior, MaxDecel (magnitude of braking behavior) and MaxLD (magnitude of steering behavior), were negatively correlated ($PCC = -0.43, p < 0.001$), suggesting that drivers who reached larger MaxLD had relatively smaller MaxDecel.

Finally, both drivers' reaction time and response intensity were very critical to collision occurrence and collision severity. The t-test showed that the the TRRT ($t = -4.4346, df = 183, p < 0.001$) and BRT ($t = -5.7096, df = 185, p < 0.001$) significantly differed between crashed and non-crashed drivers, and they were strongly correlated with collision velocity (PCC are 0.75 and 0.74, with both $p < 0.001$). The Welch's t-test result indicated that both MaxDecel ($t = -3.3641, df = 60.313, p - value = 0.001$) and MaxLD ($t = 7.8854, df = 59.291, p < 0.001$) significantly differed given whether the driver avoided the collision, and the MaxDecel also had a significant association with collision velocity (PCC = -0.5, $p <$

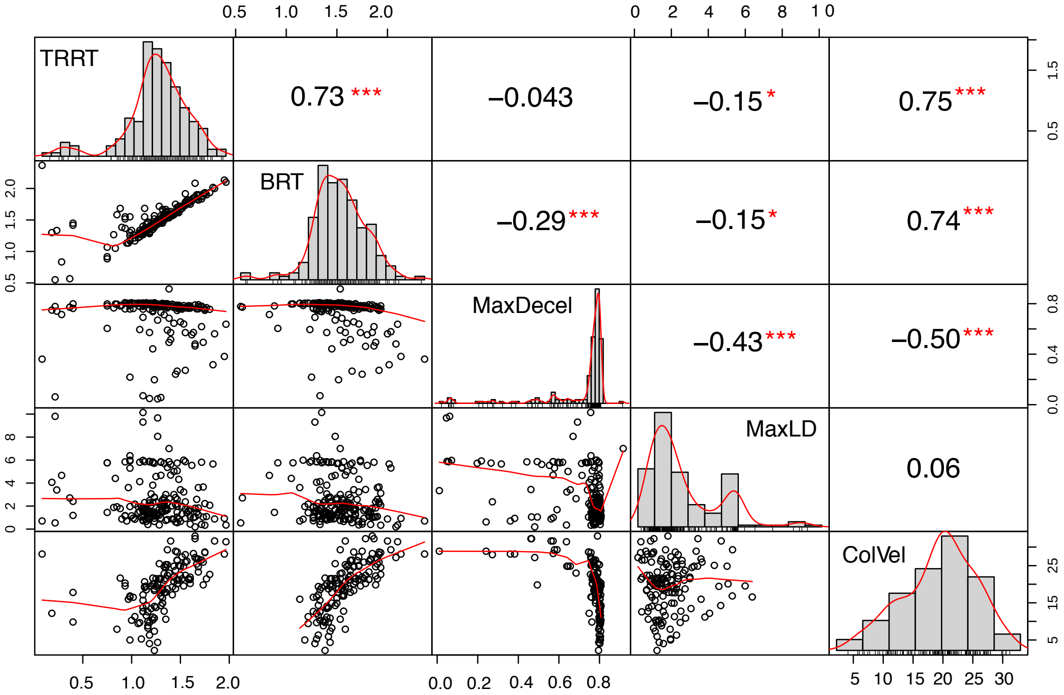
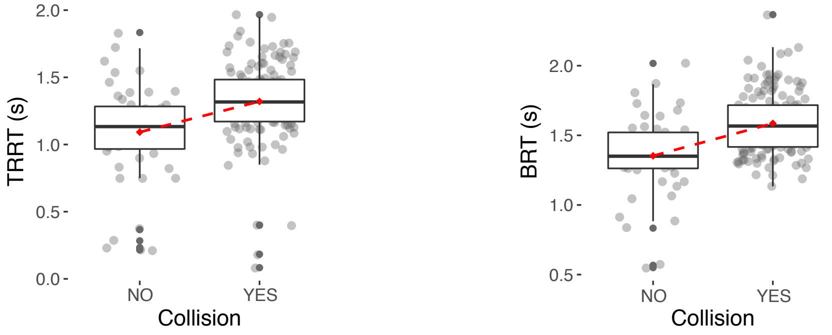


Figure 2.8: Correlation Matrix among Performance Measures

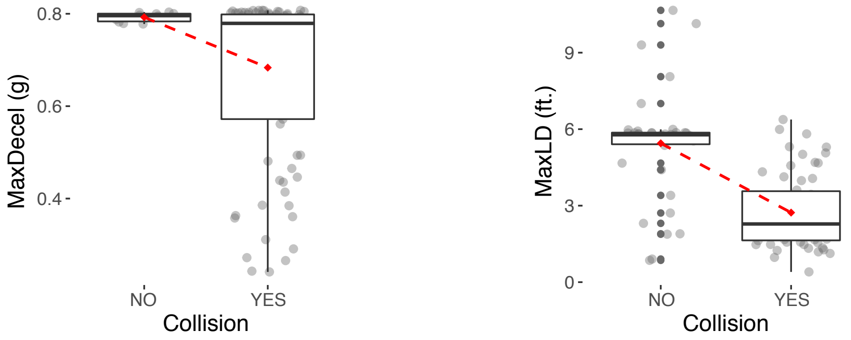
0.001). Based on Figure 2.8 and 2.9, shorter reaction time and stronger response intensity are associated with both lower likelihood of collision and lower collision velocity which suggests a reduced severity of collision.

## *2.4 Discussion*

The FCWS, which can effectively mitigate the number and severity of rear-end collisions has become standard in many cars. In 2015, over 50% of vehicles included front crash protection, and more automakers are making FCW available in new vehicles. However, a unified standard for designing and implementing the warning alert for these systems still



(a) TRRT vs. Collision (b) BRT vs. Collision



(c) MaxDecel vs. Collision (d) MaxLD vs. Collision

Figure 2.9: Behavior Measures vs. Collision Involvement

does not exist.

The primary objective of this study is to examine how acoustic characteristics of FCW alerts affect driver avoidance behavior as well as avoidance success when the driver is distracted. Fundamental frequency and duty cycle were explored in this effort, each with three levels of intensity.

This study examined five monotonous auditory tones with different acoustic characteristics manipulated and compared them to a baseline condition without warning alert in a leading vehicle decelerating scenario. In addition to collision involvement and collision velocity, these warning alerts were evaluated based on a series of avoidance behavior measures including reaction time (i.e., TRRT and BRT) and response intensity (i.e., response type, MaxDecel, and MaxLD).

A comparison between conditions with and without warning revealed that all tested FCW alerts can effectively draw drivers' attention back and assist them in avoiding the collision. The average collision rate was 69% with FCWs presented, which was a reduction of 36% compared to 94% in the condition without warning alert. The result is consistent with Lee et al. (2002), who also examined the effectiveness of early and late auditory FCW alerts. This study showed that the presented warning alerts could promote quicker throttle release and brake reaction time. Furthermore, these warning alerts produced more intense responses i.e. larger maximum brake pedal force and more substantial maximum lane deviation during the avoidance process. The result revealed that drivers' avoidance performance differed by warnings with different settings of acoustic characteristics. A more detailed comparison will be conducted in Chapter 4. The results also presented the correlations among drivers' avoidance behaviors, which provided some basis for further exploration in the causalrelationships in Chapter 4.

# Chapter 3

# STUDY TWO: SCENARIO WITH LATENT THREATS (IMA)

This chapter presents Study 2, which examined the impacts of IMA warning information on drivers' avoidance performance in a scenario with a latent threat (RLR vehicle). The data analyses in this study are based on a driving simulator study with 80 drivers, where one monotonous and three speech-based IMA warnings were examined.

## *3.1 Objective*

The objective of Study 2 is to examine the effectiveness of IMA warnings and understand how drivers' avoidance performance is affected by the presented warning information.

## *3.2 Methodology*

### *3.2.1 Participants*

All the data collection for this study was conducted in the Human Factors and Statistical Modeling Lab at University of Washington (Seattle campus). There were 80 men and women aged from 25 to 55 years old completed this study. The criterion and procedures for recruitment is highly consistent with Study 1. However, the experience in distracted driving was not required when recruiting the participants. The participants were also divided into two age groups, 25-40 and 41-55 years old with equal number of males and females.

### *3.2.2 Apparatus*

Consistent with Study 1, the NADS cab miniSims was also used for this study. When entering an intersection, drivers' ability to identify potential risk factors is crucial to ensure drivers can quickly process the dangerous situation. Eye tracking system (Zhang et al., 2016; Peng and Boyle, 2015) and video recording (Jenness et al., 2016) are typical methods for measuring visual performance. Video of the participant's face and the audio of the test procedure was recorded using a GoPro Hero3 camera at 720p resolution. The video footage of the participant's face was used to help track eye movements whether and when the driver detected the violating vehicle.

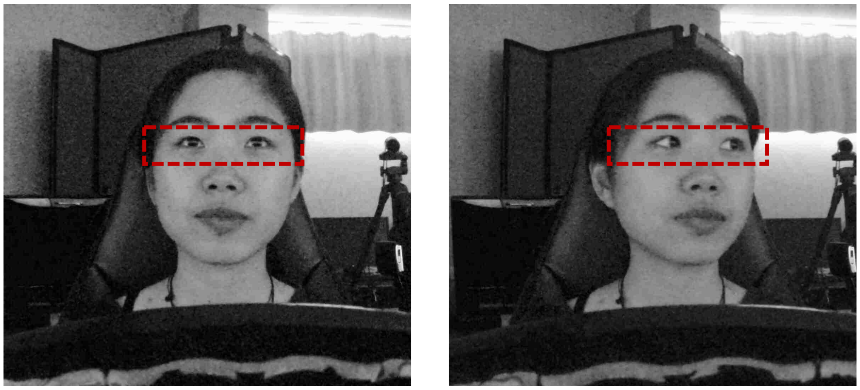


Figure 3.1: Face Video Used to Track Eye Movements

### *3.2.3 IMA Warning Alerts*

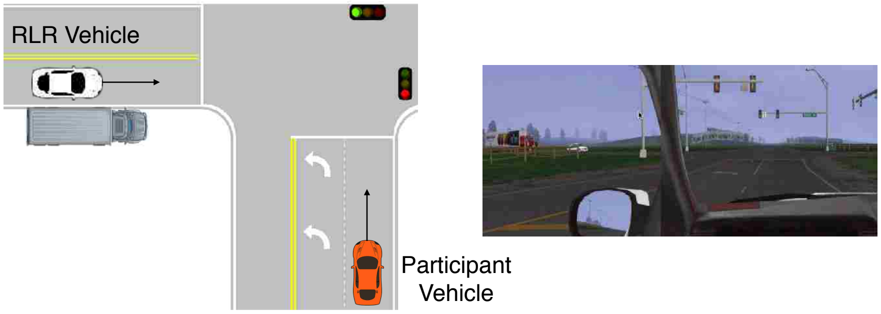
There were five auditory IMA warning conditions (Table 3.1) presented in a between-subject design (one-treatment per subject), with each participant encountering only one of the five treatment groups. One of the levels included no IMA warning and was used as a baseline condition. Three of the four warnings were speech-based and presented in a female voice, including a general warning message (Danger!), a directional message (Vehicle on your left!), and a command message(Brake now! Brake now!). There were two iterations of the directional and command messages to ensure drivers heard the message. The general warning message (Danger!) was presented three times to have it of a similar time length to the other three warnings. The fourth alert was a tone-based warning alert D,F-M that was previously shown to be effective for FCWS (Wu et al., 2018) in Study 1. An equal number of males and females from each age group were included in each treatment group.

Table 3.1: IMA Warning Conditions ($n = 16$ for each condition)

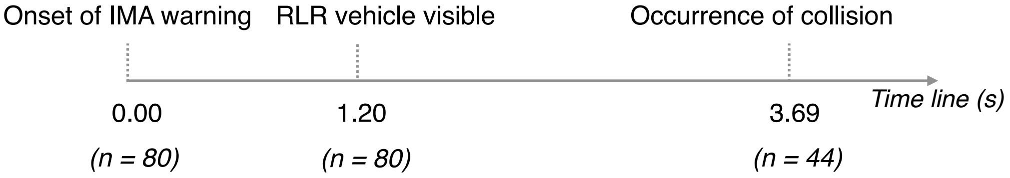
| **IMA Warning** | **Information Content** |
|---|---|
| No IMA warning | - |
| Non-Speech | "bi-bi" beep sound |
| Danger | "Danger! Danger! Danger!" |
| Direction | "Vehicle on your left! Vehicle on your left!" |
| Brake | "Brake now! Brake now!" |

### *3.2.4 Scenario*

A RLR scenario was employed in this study. In this scenario, the straight crossing paths pre-crash (Figure 3.2(a)) occurred at a signalized intersection with the incursion vehicle approaching from the left. The driving environment included a two-lane rural roadway with dry pavement in clear weather and daylight conditions. The posted speed limit was set at 45 mph.



(a) RLR scenario screenshot



(b) Timeline of key events

Figure 3.2: Red-light Running Scenario

Prior to driving, participants were instructed to follow the directional signs to a town called "Shelby". Intersections were presented at regular intervals and were preceded by directional signs to Shelby to inform participants whether to turn left, right, or continue straight. Approximately 10 to 15 minutes into the drive, the participant passed a directional sign indicating Shelby was ahead and approaches a signalized intersection with a green light. A heavy truck was on the shoulder of the crossroad to the left of the intersection blocking the driver's line of sight. An incursion vehicle appeared from the left at the same traveling speed as the participant vehicle. As the participant vehicle approaches the intersection, the IMA warning alert was triggered before the incursion vehicle could be seen by the driver. The key time points in the cross-path crash scenarios are shown in the Figure 3.2(b).

### *3.2.5 Training*

In this study, we hypothesized that the familiarization of CWSs would improve drivers' understanding of the system operation, thereby improving the driver-system interactions. Training was controlled as a factor in this experiment to examine this hypothesis. Under each warning condition, half the participants ($n = 5 \times 8 = 40$, equal number from each age group and gender) were provided a 10-minute information video that included an introduction on different in-vehicle CWSs (FCWS, LDWS, BSWS and IMA). As part of the video, situations where each warning system may be encountered was also demonstrated. The other half of participants did not receive any training.

### *3.2.6 Procedures*

Participants were told the purpose of the study is to examine differences in drivers across the U.S. After completing the Informed Consent Form (ICF),half of the participants was placed in the training condition. These participants were provided training on the operation of the CWSs though a video that was viewed before the test drive. However, all participants were not explicitly told that they would receive any type of warning during the scenario. Prior to the main data collection, participants were asked to complete a five-minutes practice drive in a similar traffic environment to familiarize themselves with the simulator environment. After completing the main drive, a debriefing statement was provided that explained the purpose of the research. Similar as in the FCW study, each participant needed to fill out a wellness questionnaire and a realism questionnaire

### *3.2.7 Response Variables*

The data from the driving simulator was collected at 60 Hz. And the face video was manually coded by frame (30 Hz). The combined simulator and video data included the following measures:

- Collision (Yes/No): for each participant, whether he/she avoided the collision was treated as an important dependent measure. The collision rate within each warning condition was also calculated.

- Avoidance Behavior: four parameters were defined and calculated to reflect drivers' avoidance behavior.

  - Response Type: the type of response driver chose to avoid the imminent collision. According to the data collected in this study, the primary responses can be accelerating or braking. But some participants did not take any responses during the test.

  - Reaction Time of Primary Response: defined by the time from the trigger of IMA warning to the moment that the driver took the primary action (tread accelerator or brake pedal).
  - Speed Change: defined as the total change in speed during the interval from the trigger of warning to the moment that collision occurred. If no collision happened, the speed change was calculated from the onset of warning to the moment that the minimum speed arrived.
  - Maximum Acceleration/Deceleration: defined as the maximum acceleration or deceleration rate during the avoidance process. It depends on each driver's response type (whether accelerating or braking).

- Eye movement: drivers' visual performance for detecting and identifying potential risk becomes the most important factor for safety driving at intersections. To investigate patterns in drivers' eye movements given different warning conditions, Zhang et al. (2016) proposed a series of dependent eye movement variables including brake or gaze at the RLR vehicle first (BOG) and time to first fixation on the RLR vehicle (TFF). Based on this study, two parameters measuring eye movements were:
  - Fixation Pattern: defined as a binary variable: 1) response before fixating on the RLR vehicle; 2) fixate on the RLR vehicle first before taking any actions.

- Time to first fixation (TFF): defined as the duration from the time when the IMA warning was trigged to the time when a driver's eye fixation at the RLR vehicle first appears (Zhang et al., 2016). This measure indicates the degree of timeliness that drivers detect the hazards

## 3.3 Results

Among the 83 participants that were recruited for this study, 80 successfully completed the test drive and their data are valid for further analysis. Based on their self-reported wellness questionnaire, 2 participants (2.4%) were withdrawn from the study because of moderate or more severe motion sickness. Another driver (1.2%) was replaced because they reported the system was not realistic.

### 3.3.1 Collision Occurrence and Collision Rate

Table 3.2: Collision Rate for Each IMA Warning Condition (n = 16 for each condition)

| IMA Warning | Collision Occurrence | Collision Rate |
|---|---|---|
| No IMA Warning | 15 | 94% |
| Non-Speech | 9 | 56% |
| Danger | 8 | 50% |
| Direction | 8 | 50% |
| Brake | 4 | 25% |

The overall collision rate was 45.3% with IMA warnings presented and 93.8% in no IMA condition (Table 3.2). The logistic regression model shows that all IMA warnings have significant impacts on the collision occurrence (Table 3.3). The speech-based warning appeared to have a better performance in reducing the likelihood of collision than monotonous warning. Compared to the no IMA condition, the odds of having a collision at the intersection would decrease by $1 - e^{-2.55} = 92\%$ if the non-speech warning was provided. The odds of collision was reduced by $1 - e^{-2.82} = 94\%$ and $1 - e^{-2.23} = 89\%$ with the Danger warning and the Direction warning presented. The odds of having a collision can be reduced by up to $1 - e^{-2.82} = 98\%$ with the Brake warning presented. Meanwhile, the training of CWSs also had a significant influence on the collision occurrence ($p = 0.05$). The odds ratio of involving in the collision between trained and untrained participants is $e^{-1.04}$= 0.35.

Table 3.3: Logistic Regression for Collision Occurrence

| **Variable** | **Estimate** | **Std. Error** | **z value** | **p-value** |
|---|---|---|---|---|
| Warning condition (baseline: no warning) | | | | |
| Non-Speech | -2.55 | 1.17 | -2.19 | 0.03 |
| Danger | -2.82 | 1.17 | -2.42 | 0.02 |
| Direction | -2.23 | 1.17 | -2.42 | 0.02 |
| Brake | -4.00 | 1.21 | -3.3 | $< 0.001$ |
| Training (baseline: No) | | | | |
| Yes | -1.04 | 0.53 | -1.98 | 0.05 |

### *3.3.2 Avoidance Behavior*

#### *Response Type*

Among the 80 participants who completed all experimental procedures, 58 used braking as the primary response to avoid colliding with the RLR vehicle. For the remaining 22 participants, 14 chose to accelerate and 8 took no actions. The Chi-square test showed that drivers' response type was strongly correlated with the warning message ($\chi^2 = 33.87, df = 9, p < 0.01$). Figure 3.3 shows the distribution of response type across different warning conditions. Over 50% participants chose accelerating and 25% participants did not take actions if no IMA was provided. Compared to the no IMA condition, most participants (86%) with IMA warning presented chose to brake since they can perceive the RLR vehicle earlier. No obvious difference was observed in the distribution of response type between conditions with the non-speech warning and the Danger warning. However, all the drivers given the Brake warning chose braking to avoid the impending collision.

Age group and gender did not show significant effects on drivers' response type. The training of CWSs did not appear to have a significant impact on the response type neither.

#### *Reaction Time of Primary Response*

For participants who took actions to avoid the potential collision, their reaction time to press the accelerator or brake pedal from the onset of IMA warning was analyzed. For drivers that did not take actions, no valid reaction time was obtained and was excluded from the analysis of this measure. The multivariate regression result indicates that the warning

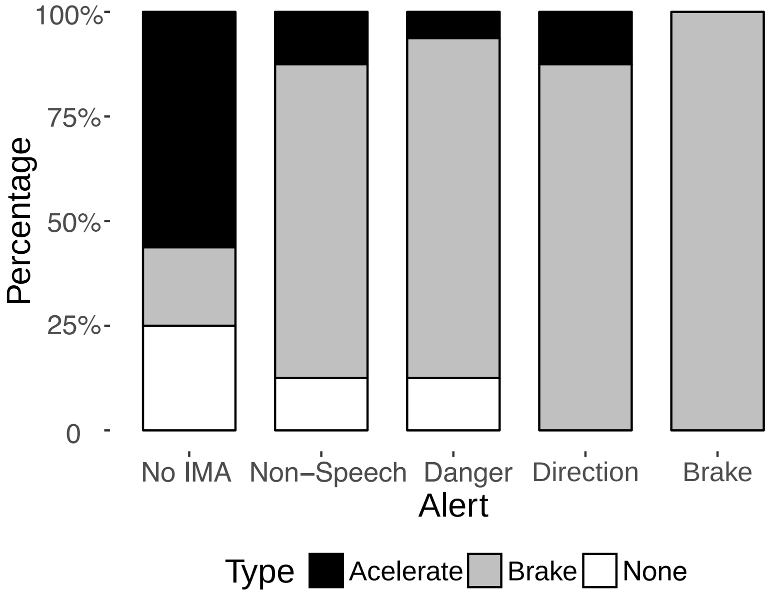


Figure 3.3: Response Type across IMA Warnings

condition had a significant influence on how quickly a driver responded. Table 3.4 shows that all presented IMA warnings can considerably reduce drivers' reaction time compared to the no IMA condition (all the p values are less than 0.01). Among the four IMA warnings, the Brake warning performed best on average in shortening reaction time.

The regression result also indicates that the reaction time was significantly affected by whether a driver received the training ($p < 0.001$) and the driving speed when the warning was issued. Compared to untrained drivers, drivers who received the training had approximately 0.6 s lower reaction time on average. Based on the coefficient, drivers' reaction time would increase by 0.06 s if their driving speed goes 1 mph up.

Table 3.4: Multivariate Regression for Reaction Time

| **Variable** | **Estimate** | **Std. Error** | **z value** | **p-value** |
|---|---|---|---|---|
| Intercept | 0.152 | 1.250 | 0.122 | 0.903 |
| **Warning condition** (baseline: no warning) | | | | |
| Non-Speech | -0.684 | 0.265 | -2.581 | 0.012 |
| Danger | -0.797 | 0.268 | -2.980 | $< 0.001$ |
| Direction | -0.894 | 0.253 | -3.533 | $< 0.001$ |
| Brake | -1.214 | 0.254 | -4.774 | $< 0.001$ |
| **Training** (baseline: No) | | | | |
| Yes | -0.608 | 0.157 | -3.877 | $< 0.001$ |
| **Speed at Warning** | 0.060 | 0.026 | 2.268 | 0.027 |

*Speed Change*

The mitigation in crash severity is another important measure to assess effectiveness of CWS . The severity of a collision is directly influenced by the collision velocity. Hence, the total speed change during the avoidance process was measured and examined. Due to the heterogeneity of this measure ($Levene's\ Test : p < 0.001$), the Welch-James ANOVA for heterogeneous variances was conducted. The result reveals that the speed change was significantly impacted by the warning information ($\chi^2 = 147.81, df = 4, p < 0.001$). The IMA warnings can effectively enlarge the change in speed, with the Brake warning contributed the greatest speed change (31.8 mph on average).

Table 3.5: Mean and Std. Deviation of Total Speed Change

| | | **Mean** | **Std. Deviation** |
|---|---|---|---|
| **Alert** | No IMA Warning | 1.652 | 2.341 |
| | Non-speech | 19.573 | 16.359 |
| | Danger | 20.544 | 17.941 |
| | Direction | 19.830 | 16.871 |
| | Brake | 31.813 | 12.467 |

The result of Welch-James test also indicates there existed an interaction between warning condition and training. Compared to speech-based warnings, a greater difference in speed change was observed between trained and untrained drivers in non-speech warning condition. With this IMA warning presented, drivers who received training had larger speed changes (Figure 3.4) .

### *Maximum Acceleration/Deceleration (Max Accel/Decel)*

In addition to response type and speed change, the Max Accel/Decel (depends on the response type) during the avoidance process was also examined, which provides a deeper and more complete insight into drivers' avoidance response. Figure 3.5 displays the mean and std. deviation of Max Accel/Decel across warning conditions and gender. Compared to the no IMA condition, the Max Accel/Decel considerably increased when IMA warnings were pro-

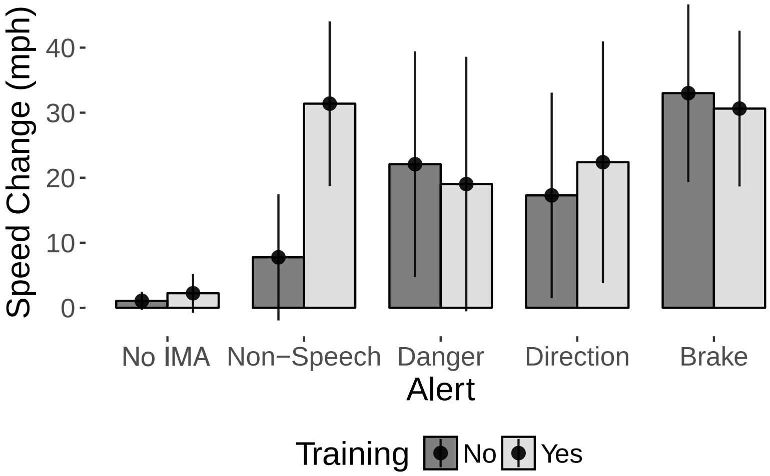


Figure 3.4: Average Speed Change across Warning and Training Condition

vided. Since most drivers under the Brake warning braked hard (88% over 0.8g), the largest average Max Decel was obtained in this warning condition. Based on Figure 3.5, male drivers generally braked harder and had larger Max Accel/Decels than female drivers. This is consistent with the multivariate regression result (Table 3.6) that, the Max Accel/Decel was significantly impacted by the IMA warning and gender. The regression result also shows a trend that the driving speed may have a slightly negative impact on the Max Accel/Decel ($p = 0.089$).

### *3.3.3 Eye movements*

#### *Fixation Pattern*

Two fixation patterns: fixation first and response first were identified in this study and their distributions across warning conditions are displayed in Figure 3.6(a). Compared to the no

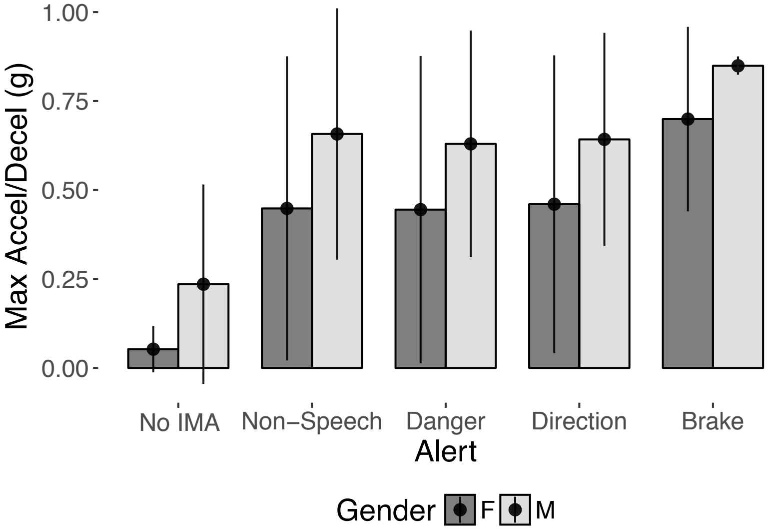


Figure 3.5: Average Max Accel/Decel Across Warning and Training Condition

IMA condition with only a small portion of drivers responded first, the portion of drivers that responded first increased when IMA warnings were offered. However, given the Brake warning, all the participants braked first before fixating on the RLR vehicle. Figure 3.6(b) shows that drivers who received training were more likely to response before fixating on the RLR vehicle. Compared to female drivers, male drivers also tend to be more likely to response first (see Figure 3.6(c)).

Given the number of drivers within each combination of IMA warning, gender, training and fixation pattern, a log-linear analysis was conducted with a likelihood-ratio test ($G - test$). The results indicate that the IMA warning ($G^2 = 31.31, df = 8, p < 0.001$) is significantly associated with the fixation pattern. There are also some trends noted with gender ($G^2 = 3.37, df = 1, p = 0.06$) and training ($G^2 = 3.37, df = 1, p = 0.06$) associated with the fixation pattern.

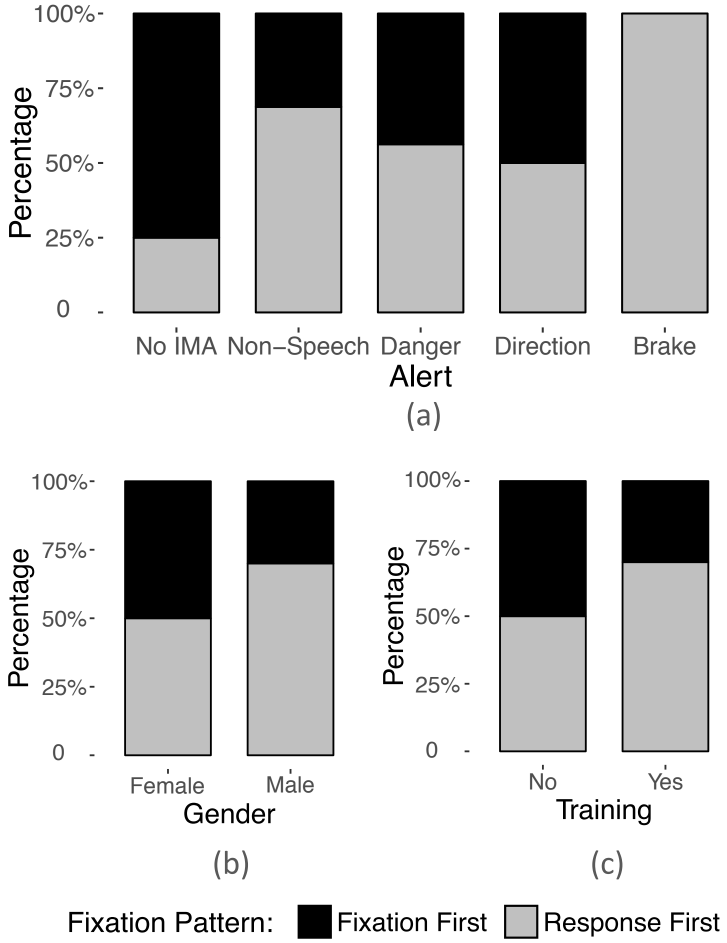
Table 3.6: Multivariate Regression for Max Accel/Decel

| **Variable** | **Estimate** | **Std. Error** | **z value** | **p-value** |
|---|---|---|---|---|
| Intercept | 1.020 | 0.567 | 1.800 | 0.076 |
| **Warning condition** (baseline: no warning) | | | | |
| Non-Speech | 0.376 | 0.210 | 3.431 | $< 0.001$ |
| Danger | 0.340 | 0.112 | 3.028 | 0.003 |
| Direction | 0.397 | 0.108 | 3.673 | $< 0.001$ |
| Brake | 0.604 | 0.109 | 5.546 | $< 0.001$ |
| **Gender** (baseline: Female) | | | | |
| Male | 0.158 | 0.070 | 2.275 | 0.026 |
| **Speed at Warning** | -0.020 | 0.012 | -1.725 | 0.089 |

*Time to First Fixation (TFF)*

Table 3.7 displays the multivariate regression result for TFF that depicts how quickly a driver detected the RLR vehicle. The result suggests the non-speech warning ($p = 0.027$), the Danger warning ($p < 0.001$) and the Direction warning ($p < 0.001$) can significantly reduce TFF by 0.495 s, 0.897 s and 1.027 s on average compared to the no IMA condition. However, the Brake warning did not contribute a significant decrease in TFF.

The result also shows the training may help shorten the TFF. But, the effect of training appeared to vary given different IMA warnings: a greater TFF reduction by training was



(a)

(b)

(c)

Figure 3.6: Fixation Patterns Based on Warning Condition (a), Gender (b) and Training (c)

observed in the non-speech warning condition compared to the case in speech-based warning conditions (Figure 3.7).

### *3.3.4 Correlations among Performance Measures*

Since the hazard is hidden to drivers, their avoidance process to avoid the potential collision is very complex with interacted behaviors and should be different from that in the FCW

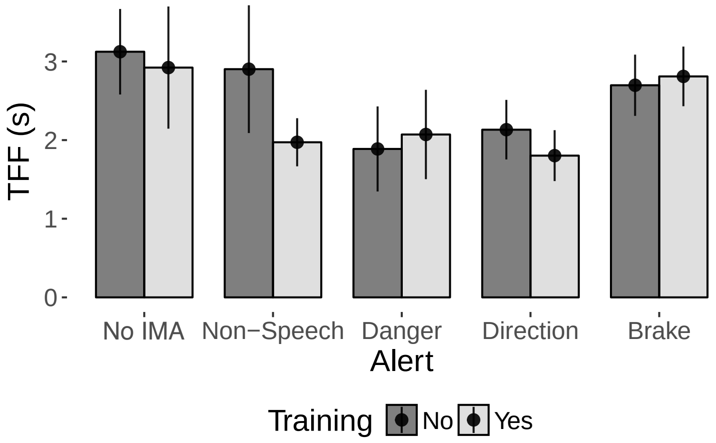


Figure 3.7: Average TFF Across Warning and Training Condition

Table 3.7: Multivariate Regression for TFF

| **Variable** | **Estimate** | **Std. Error** | **z value** | **p-value** |
|---|---|---|---|---|
| Intercept | 0.858 | 0.991 | 0.866 | 0.390 |
| **Warning condition** (baseline: no warning) | | | | |
| Non-Speech | -0.495 | 0.191 | -2.592 | 0.011 |
| Danger | -0.897 | 0.196 | -4.586 | $< 0.001$ |
| Direction | -1.027 | 0.188 | -5.450 | $< 0.001$ |
| Brake | -0.198 | 0.190 | -1.041 | 0.301 |
| **Training** (baseline: No) | | | | |
| Yes | -0.207 | 0.119 | -1.733 | 0.087 |
| **Speed at Warning** | 0.056 | 0.020 | 2.760 | 0.007 |

scenario. Figure 3.8 displayed the correlation matrix between each pair of the performance measures that were analyzed in the last section, indicating strong associations among drivers' avoidance behaviors in this scenario. According to Figure 3.8 and 3.9, driver's eye movements are correlated with drivers' avoidance behaviors. Based on the Welch's t-test, drivers who responded first have significantly shorter reaction time ($t = 5.7254, df = 29.055, p < 0.001$), greater speed change ($t = -8.26, df = 77.999, p < 0.001$) and Max Accel/Decel ($t = -8.1641, df = 63.035, p < 0.001$). Drivers' TFF is positively correlated with their reaction time (PCC = 0.44, $p < 0.001$), but negatively correlated with their speed change (PCC = -0.35, $p < 0.001$) and Max Accel/Decel (PCC = -0.36, $p < 0.001$). Drivers' reaction time during the avoidance process was also significantly associated with the speed change (PCC = -0.71, $p < 0.001$) and Maximum Accel/Decel rate (PCC = -0.71, $p < 0.001$), with shorter reaction time associated with larger speed change and larger Maximum Accel/Decel. In addition, the correlation analysis reveals a strongly positive correlation between drivers' total speed change and Maximum Accel/Decel (PCC = 0.91, $p < 0.001$).

Similarly as in the FCW study, drivers' reaction time and response behavior also play crucial roles in avoidance success in IMA scenario. The Welch's t-test showed that drivers' reaction time ($t = 11.216, df = 113.89, p < 0.001$), speed change ($t = -7.0254, df = 39.279, p < 0.001$) and Max Accel/Decel ($t = 9.361, df = 68.494, p < 0.001$) significantly differed given whether they avoided the collision. Based on Figure 3.8, shorter reaction time, greater speed change and greater Max Accel/Decel can be observed if a driver successfully avoided the collision.

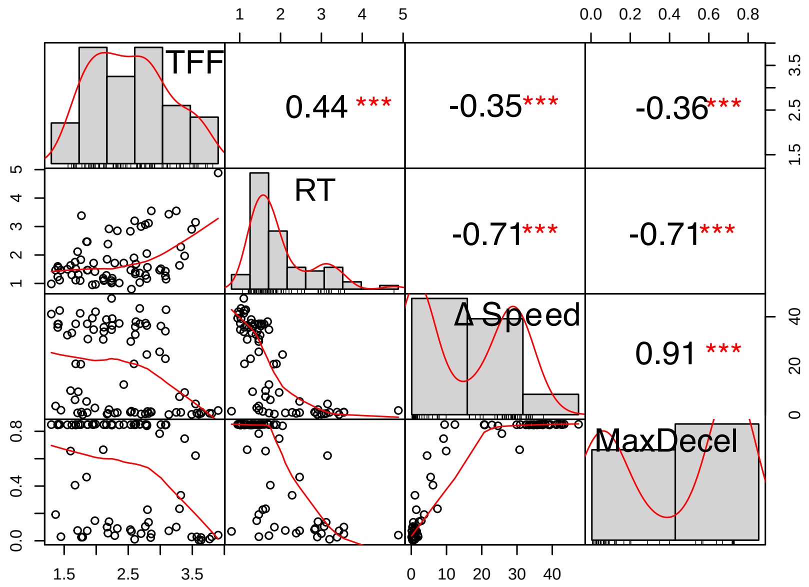
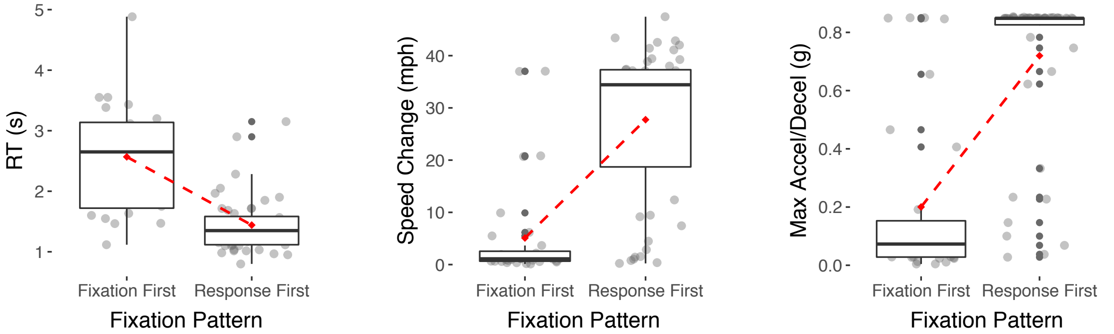


Figure 3.8: Correlation Matrix among Performance measures (continues variables)

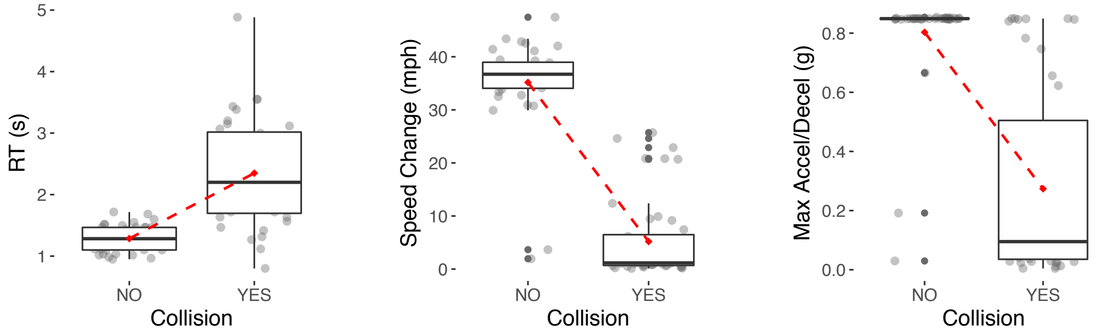


(a) RT vs. Fixation Pattern (b) Speed Change vs. Fixation Pattern (c) Max Accel/Decel vs. Fixation Pattern

Figure 3.9: Avoidance Behavior vs. Fixation Pattern

## *3.4 Discussion*

In contrast to FCW which is aimed at addressing apparent hazards for distracted drivers, the IMA warning can assist drivers in detecting a more hidden hazard and responding more



(a) RT vs. Collision (b) Speed Change vs. Collision (c) Max Accel/Decel vs. Collision

Figure 3.10: Avoidance Behavior vs. Collision Involvement

timely to the hazard. This study evaluated four auditory IMA warnings including one monotonous and three speech-based messages in a RLR scenario. In the scenario with latent hazards, drivers' visual performances such as hazard-detection abilities and fixation allocation are critical to the success of avoidance. Hence, in addition to collision occurrence and avoidance behavior (i.e., reaction time, response type, Max Decel/Accele, and Speed Change), this study also examined drivers' eye movements (fixation pattern and TFF) during their avoidance process. The correlations among avoidance success, drivers' eye movements, and their avoidance behavior were also examined. However, the collision velocity of participant vehicle was not discussed in this study, because the participant vehicle was hit on the side by the RLR vehicle over 80% of cases in this scenario. For a right angle collision, the severity of collision was more determined by the velocity of incursion vehicle (RLR vehicle) which was manipulated by the scenario.

The results show that all the presented IMA warnings were effective in enhancing drivers' avoidance performance and could help drivers avoid the potential collision. This was observed by the lower collision rates and lower likelihoods of collision compared to no IMA condition. Similar benefits were found in previous studies (Yan et al., 2014; Zhang et al., 2016).

Among these IMA warnings, the Brake warning had the lowest collision rate and encouraged drivers to respond with the most appropriate action (braking) more timely. However, drivers' hazard-detection abilities were not enhanced by this warning based on TFF. This is because most drivers in this condiiton followed the instruction and braked immediately after the issue of warning. Both the Danger warning and the Direction warning can effectively provide clues for drivers to detect the RLR vehicle and guide their attention towards the RLR vehicle more quickly.

Previous studies have shown that familiarization on CWSs can enhance drivers' trust in the system and help them better understand its operation (Koustanai et al., 2010; Koustanaï et al., 2012). This study also confirm that drivers who received the video training of CWSs were more likely to avoid the collision and have a shorter reaction time. Furthermore, the effect of training was found to differ across warning conditions. With the non-speech IMA warning presented, the training can prompt drivers to detect the RLR vehicle earlier and avoid the imminent collision with better performances (i.e., greater speed change).

## Chapter 4

# CAUSAL RELATIONSHIPS BETWEEN WARNINGS AND AVOIDANCE BEHAVIOR

This chapter investigates the causal relationships among warnings, drivers' behavior and collision occurrence for both FCW and IMA systems. The effects of presented warnings were compared and exmained.

### *4.1 Partial Least Squares Path Modeling*

Studies show that in-vehicle warning information can reduce collision occurrence (McGehee et al., 2002; Lewis et al., 2017) and invoke a positive change in driving performance (Lee et al., 2002; Bakowski et al., 2015). However, the underlying mechanism of collision avoidance still remains unclear and need to be further understood. Traditional regression models are only able to reveal simple relationships between the response and each explanatory variable, but the associations from these models lack insights on causal inference.

Popular causal analysis techniques such as Bayesian networks, Structural equation modeling (SEM) and Partial least squares (PLS) path modeling may help reveal the causal relationships among drivers avoidance behavior. The Bayesian network displays the causal map as a directed acyclic graph (DAG), and represents a series of conditional independence constraints among the variables and their related conditional probability distributions (Lauria and Duchessi, 2007). Networks where discrete variables have continuous parents are not allowed (Cobb et al., 2007) and most theory and methods were developed for the case in which all the variables are discrete. However, continuous and discrete variables coexist in this study. We need to discretized all the continuous variables; this requires a cost in precision.

The use of SEM enjoys the advantage over traditional data analytic techniques such as standard regression analysis, as it allows for estimation of an entire structural framework rather than mere testing individual hypotheses. It has been widely used in social science, economics and marketing, but has gained attention in the transportation area for understanding complex causal relationships as observed in human behavior (Yan et al., 2014; Hassan and Abdel-Aty, 2011). Partial least squares (PLS), a path modeling approach that shows cause-effect among latent variables while also generating path coefficients, is very similar to SEM. However, PLS offers several advantages over SEM such as the ability to use lower sample size, more relaxed assumptions, and the capability to handle formative indicators (Shackman, 2013). Compared to SEM, which typically requires at least 200 samples (Kline, 2015), PLS employs a different algorithm involving principal component analysis (PCA) rather than maximum likelihood factor analysis, which can get better solutions with smaller sample sized. Computations in SEM assume that the data are normally distributed but this is not an assumption for the parameter estimation in PLS. Also, PLS is considered more appropriate for exploratory research where theory is at an early stage of development. While, SEM is considered to be more useful when theory is completed and needs to be further confirmed (Shackman, 2013). Moreover, PLS have both reflective and formative scales, whereas SEM is designed mostly for reflective scales. Hence, the PLS path modeling was considered more suitable in this study to explore the causal relationships among drivers' avoidance behavior.

A PLS path model is composed of two sets of linear equations: the inner model and the outer model (see Figure 4.1). The inner model specifies the relations between latent variables, while the outer model specifies the relations between a latent variable and its indicators or manifest variables (Henseler and Sarstedt, 2012).

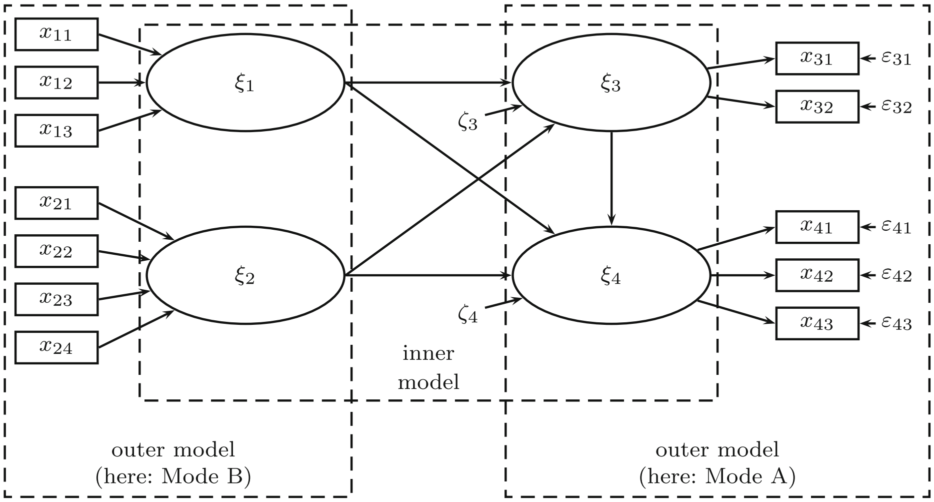


Figure 4.1: The Structure of PLS Path Model (Henseler and Sarstedt, 2012)

PLS path modeling includes two different modes of outer models: Mode A optimizing a covariance criterion (Tenenhaus and Tenenhaus, 2011) and Mode B optimizing a correlation criterion (Hanafi, 2007). The choice of a certain mode is subject to statistical and theoretical reasoning, and typically results from a decision to define an outer model as reflective (Mode A) or formative (Mode B) (Fornell and Bookstein, 1982). In the reflective mode, manifest variables are considered being caused by the latent variables. In the formative mode of an outer model, the latent construct is considered to be formed by its indicators. The main difference between the reflective and formative is associated with the causal-effect relationships between the indicators and the constructs (the direction of the arrows).

The main purpose of the PLS path model is to evaluate both the inner and outer models. In a PLS path model diagram, arrows show causations among the variables and the relationship is defined by the direction of the arrow, i.e. variables receiving the arrow are to be considered as endogenous variables in the specific relationship. Endogenous variables can be influenced by exogenous variables directly or indirectly.

In this study, the PLS path modeling technique is adopted to further investigate the effectiveness of warning alerts. In particular, we focus on assessing the structure and path coefficient value in the inner-model, which reflects the causal relationships between warning condition, driver characteristics, driving behavior and collision avoidance outcome. The models were constructed for the analysis using the 'plspm' package in R.

## *4.2 FCW: Scenario with Apparent Threats*

The first PLS path model was developed considering only the warning versus no warning condition in order to analyze the causal relationships between collision avoidance behaviors (response intensity and reaction time) as well as the entire interaction among collision avoidance behaviors, warning conditions, and collision occurrence. Figure 4.2 shows the results of the PLS path model. The shaded area are the inner-model reflecting the causal relationships among latent variables. In the inner-model, the warning condition (w/ FCW or w/o FCW) and TTCatAlert is an exogenous variable, reaction time and response intensity are intermediate variables, and whether a collision occurred is an endogenous variable. The line width of the arrows between two latent variables reflect the magnitude of the path coefficients. The arrows are colored in blue when the path coefficients are negative. The other arrows are in black, meaning positive loadings. The outer-model(non-shaded area) shows the breakdown of the three latent variables personal information (formative mode), reaction time (reflective mode) and response intensity (formative mode), and the indicators reflecting or contributing to them.

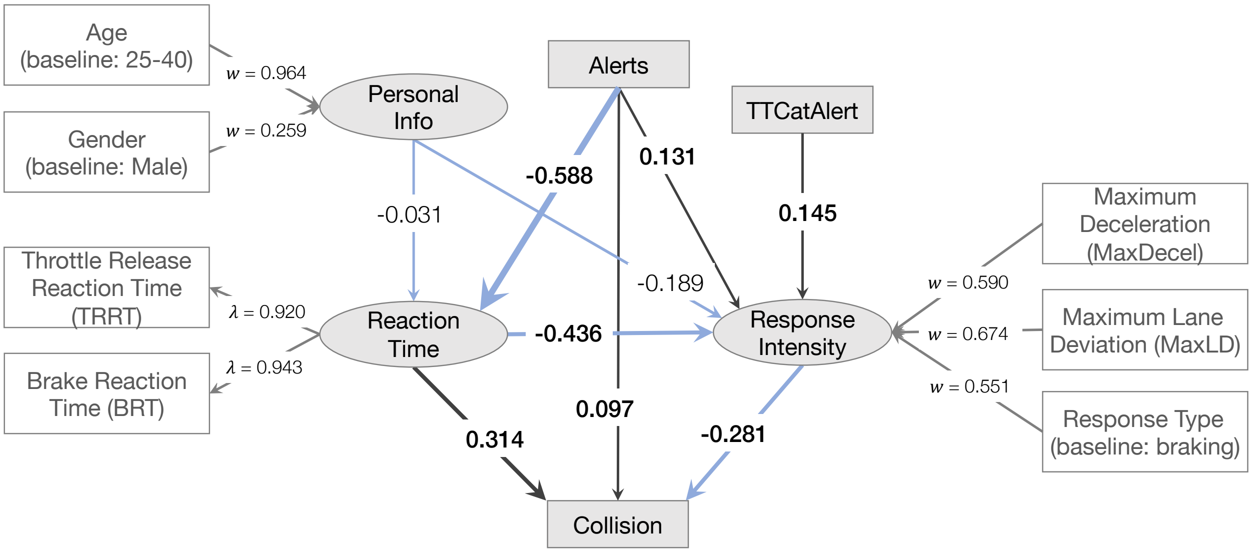


Figure 4.2: PLS Path Model for All FCW Alerts. Line width reflects the magnitude of the path coefficients, and line color reflecting whether the path coefficients are positive (black) or negative (blue).

Since PLS path modeling does not rely on any distributional assumptions, significance levels for the parameter estimates (based on normal theory) are not suitable. Instead, the resampling procedure, bootstrapping was employed to obtain information about the variability of the parameter estimates. Table 4.1 shows the 95% bootstrapping confidence interval (CI) for each estimate of the path parameter. In the inner-model shown in Figure 4.2, the path coefficients which are statistically significant ($\alpha = 0.05$) are presented in bold.

Table 4.1: 95% CI for path coefficients based on bootstrapping

| | Original | Mean.Boot | Std.Error | 95% CI |
|---|---|---|---|---|
| Alert ->Reaction Time | -0.588 | -0.595 | 0.064 | (-0.702, -0.451) |
| Alert ->Response Intensity | 0.131 | 0.150 | 0.112 | (0.006, 0.313) |
| Alert ->Collision | 0.097 | 0.102 | 0.066 | (0.019, 0.203) |
| Personal Info ->Reaction Time | -0.031 | 0.002 | 0.076 | (-0.140, 0.143) |
| Personal Info ->Response Intensity | -0.189 | -0.126 | 0.154 | (-0.302, 0.258) |
| TTCatAlert ->Response Intensity | 0.145 | 0.145 | 0.062 | (0.019, 0.245) |
| Reaction Time ->Response Intensity | -0.436 | -0.428 | 0.095 | (-0.597, -0.236) |
| Reaction Time ->Collision | 0.314 | 0.321 | 0.107 | (0.114, 0.523) |
| Response Intensity ->Collision | -0.281 | -0.277 | 0.106 | (-0.465, -0.058) |

The results of the PLS path model shown in Figure 4.2 indicate that the effect of warning condition on collision occurrence is composed of direct and indirect effects. Compared to the direct effect, the indirect effects from reaction time and response intensity are much stronger. Warning condition directly affects reaction time, having a negative impact that is statistically significant ($factor\ loading = -0.588$). This indicates that these FCW alerts decreased reaction time. Reaction time directly impacts the intensity of response and likelihood of collision. Reaction time has a significantly positive effect on collision occurrence ($factor\,loading = 0.314$), indicating a longer reaction time contributes directly to a higher likelihood of rear-end collision. Reaction time has a significantly negative effect on response intensity, indicating shorter reaction time leads to more intense responses such as more complex response, larger maximum deceleration or larger lane deviation. Moreover, the driving condition (TTCatAlert) when FCW is issued also has a significant impact on drivers' response intensity ($factor\,loading = 0.145$), with larger TTC allowing more intense responses.

The warning condition indirectly affects response intensity, but there is no significant direct impact. A more intense response can help avoid the collision (as noted by the statistically significant negative effect, $factor\,loading = -0.281$). In addition, while personal characteristics impacted reaction time and response intensity, the observed differences are small and not statistically significant.

For each tested FCW alert, an individual PLS path model was constructed to identify the impact of each alert on avoidance behavior and collision occurrence. Figure 4.3 displays the each inner-model of all five PLS path models. All five models share the same structure, with the only difference being the path coefficients. Same as the model in Figure 4.2, the line width reflects the magnitude of the path coefficients and all the significant ($\alpha = 0.05$) path coefficients are presented in bold. The positive coefficients are presented in black while the negative coefficients are in blue. The results of the five models show that every tested

FCW alert can significantly reduce drivers' reaction times. As seen in the first PLS model considering all FCW alerts, a shorter reaction time will lead to a more intense response and reduced collision occurrence. The intensity of drivers' response also has an impact on the collision occurrence, but this impact was not statistically significant in the condition with alert D,F-M or D-L presented.

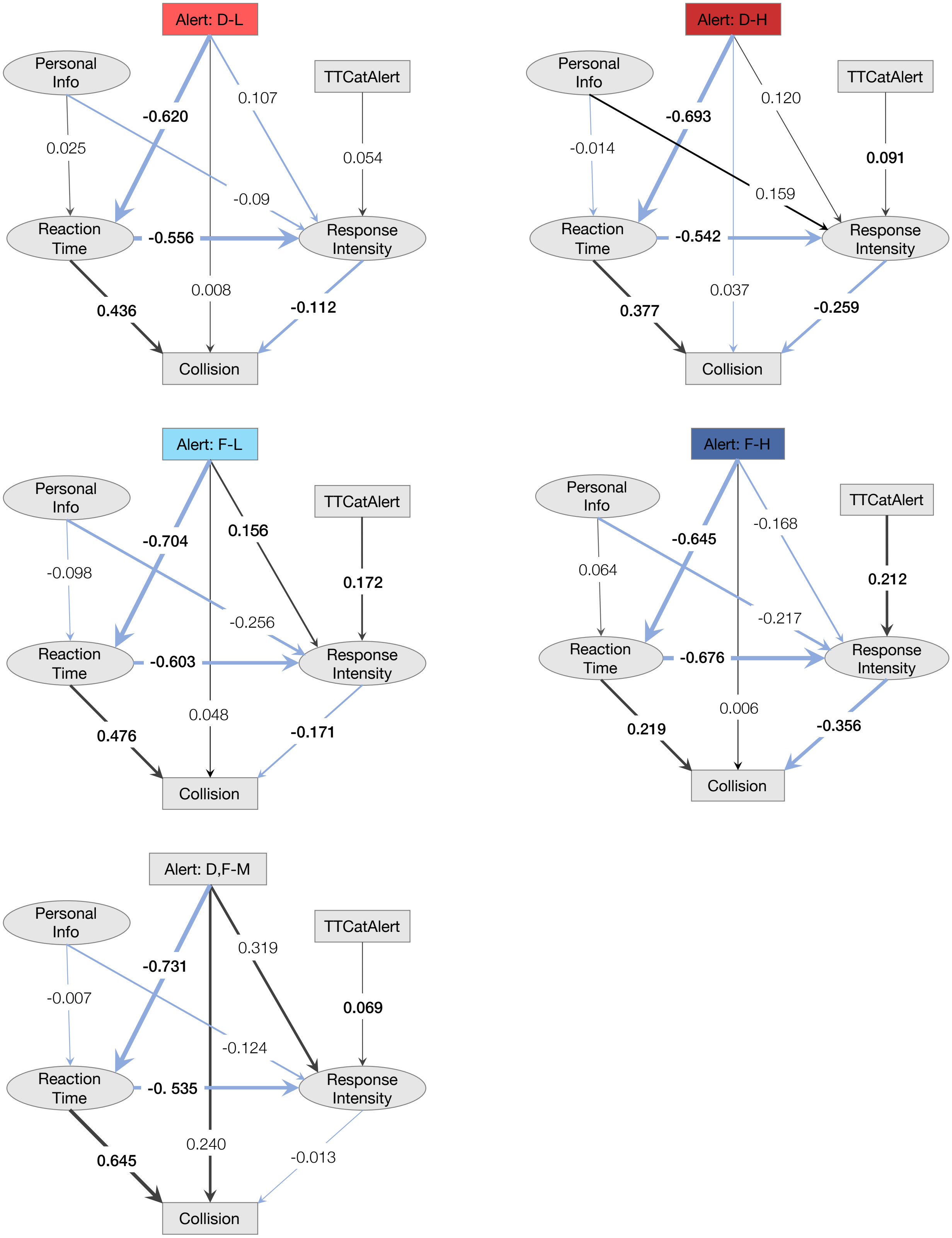


Figure 4.3: PLS Path Models (inner-models) for Each FCW Alert

To better compare these FCW alerts, the total effect of each alert on avoidance behavior and collision occurrence was calculated. This effect (Figure 4.4) was calculated as the sum of the direct and indirect effects of the path coefficients from each model.

The alerts D,F-M and F-L were best in decreasing reaction times and increasing response intensity (Figure 4.4). F-L also has the best performance in reducing the final collision occurrence. In contrast, F-H and D-L performed the worst in producing shorter reaction times, more intense responses, and promoting collision avoidance success.

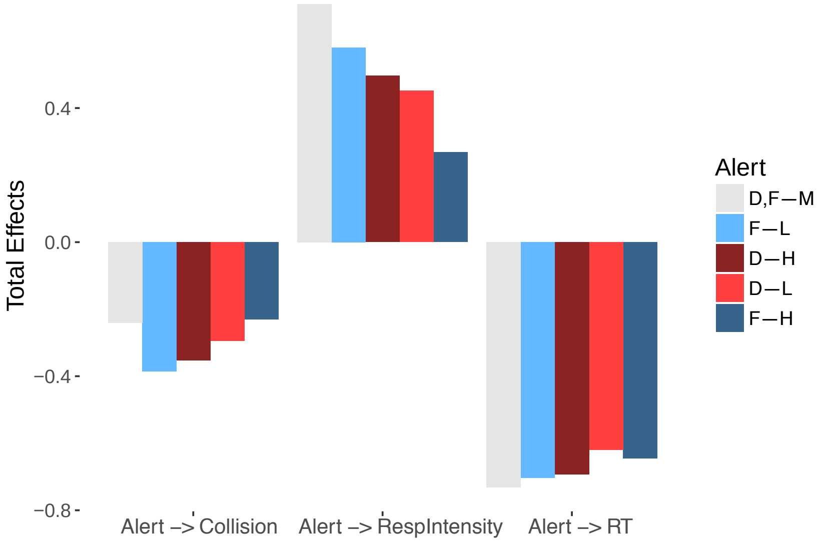


Figure 4.4: Total Effects: Direct + Indirect Effects for Each FCW Alerts

### 4.3 *IMA: Scenario with Latent Threats*

Similar as the procedures to develop the FCW models, a general model considering only the IMA warning versus no warning was constructed to investigate the causal relationship among warning condition, eye movements, collision behavior and collision occurrence. Figure 4.5

shows the result of this PLS path model. In this inner-model, the IMA warning, training and personal information are exogenous variables, eye movements, reaction time and avoidance response are intermediate variables, and collision occurrence is an endogenous variable. And breakdown of the latent variables including personal information, eye movements and response behavior are shown in the outer-model. Table 4.2 shows the variability of the path parameter estimates based on bootstrapping. The path coefficients which are statistically significant are displayed in bold in Figure 4.5.

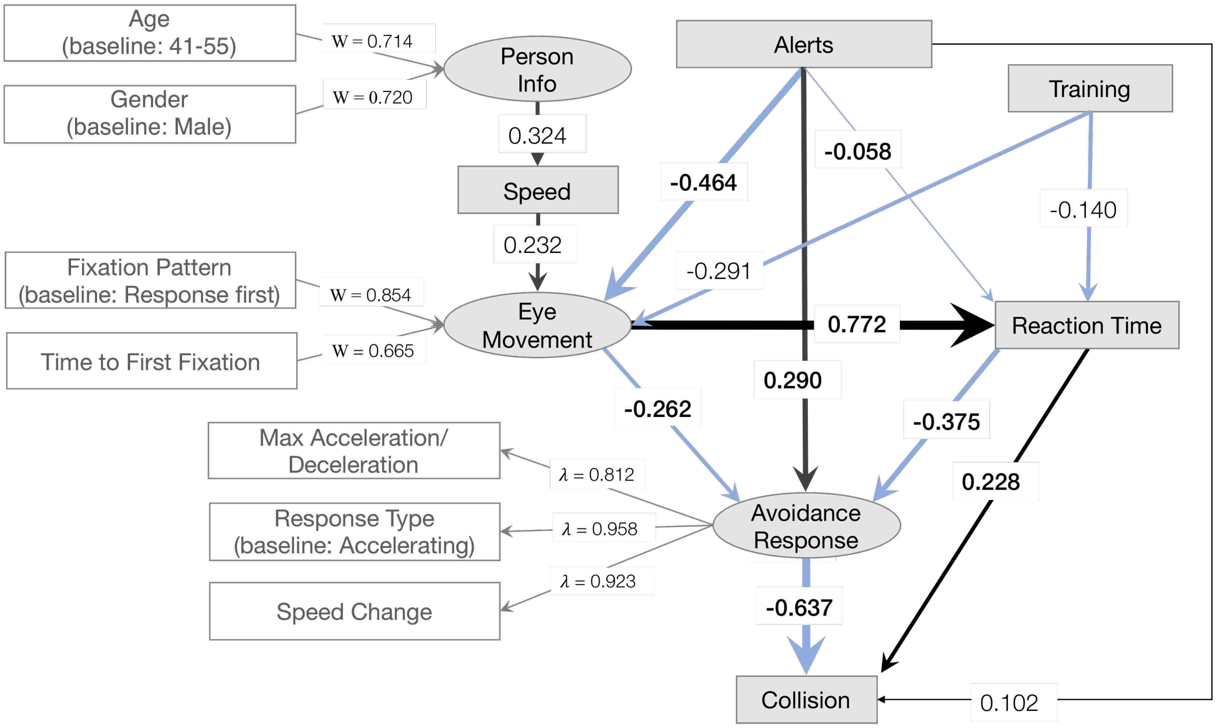


Figure 4.5: PLS Path Model for All IMA Alerts. Line width reflects the magnitude of the path coefficients, and line color reflecting whether the path coefficients are positive (black) or negative (blue).

The new PLS path model reveals that the effect of IMA warning on collision occurrence

Table 4.2: 95% CI for IMA path coefficients based on bootstrapping

| | Original | Mean.Boot | Std.Error | 95% CI |
|---|---|---|---|---|
| Alert ->Eye Movement | -0.464 | -0.467 | 0.094 | (-0.642, -0.283) |
| Alert ->Reaction Time | -0.058 | -0.061 | 0.100 | (-0.292, -0.003) |
| Alert ->Avoidance Response | 0.290 | 0.272 | 0.129 | (0.002, 0.504) |
| Alert ->Collision | 0.102 | 0.116 | 0.110 | (-0.077 , 0.350) |
| PersonalCH ->TTC | 0.324 | 0.000 | 0.357 | (-0.496, 0.494) |
| Training ->Eye Movement | -0.291 | -0.289 | 0.087 | (-0.456, -0.112) |
| Training ->Reaction Time | -0.140 | -0.138 | 0.062 | (-0.255, -0.014) |
| SpeedAtAlert ->Eye Movement | 0.232 | 0.232 | 0.104 | (0.022, 0.432) |
| Eye Movement ->Reaction Time | 0.772 | 0.762 | 0.083 | (0.574, 0.894) |
| Eye Movement ->Avoidance Response | -0.262 | -0.257 | 0.130 | (-0.522, -0.011) |
| Reaction Time ->Avoidance Response | -0.375 | -0.398 | 0.150 | (-0.698, -0.104) |
| Reaction Time ->Collision | 0.228 | 0.227 | 0.127 | (0.001, 0.500) |
| Avoidance Response ->Collision | -0.637 | -0.649 | 0.138 | (-0.918, -0.370) |

is also comprised of direct and indirect effects. And the indirect effect, which is by impacting eye movements, reaction time, and avoidance response, plays a much more important role in determining the avoidance success than the direct effect. Based on this model, the IMA warning has direct impacts on eye movements, which is negative and statistically significant. This indicates that the IMA warnings decreased TFF and prompted drivers to responded first(before fixation on the RLR vehicle). Eye movements have a significantly positive impact on reaction time, indicating longer TFF and fixation on the RLR vehicle before response would lead to a longer reaction time. Eye movements also directly affect response behavior with a significantly negative impact. This suggests shorter TFF and the fixation pattern of response first would prompt a more intense and valid response with larger maximum deceleration/acceleration and greater speed change.

In addition to the indirect effect from eye movements, the IMA warnings also affect reaction time directly, leading to a shorter reaction time. Reaction time has directly negative impacts on drivers' avoidance response, suggesting shorter reaction time leads to a more intense and valid avoidance response. The IMA warnings also have a direct impact on drivers' response behavior and this direct impact is positive and statistically significant.

Moreover, the model result shows that the training has a significantly negative impact on eye movements and reaction time. This indicates that training can directly help reduce TFF and reaction time, and induce drivers to respond first. Additionally, driving speed also has a significant influence on drivers' eye movements and their reaction time, with lower speed allowing shorter TFF, shorter reaction time and higher likelihood of responding before detecting the RLR vehicle.

Consistent with the FCW model, reaction time has a significantly positive effect on collision occurrence, while avoidance response has a significantly negative effect on collision occurrence. This indicating a shorter reaction time and a more intense or valid avoidance response would contribute to smaller likelihoods of colliding with the RLR vehicle.

An individual PLS path model with the same structure was developed for each IMA warning to pinpoint the its effects on eye movements, avoidance behavior and collision occurrence. Same as Fig4.2, 4.3, 4.5, the line width and line color demonstrate the magnitude and sign (positive or negative) of the path coefficients and all the significant coefficients are presented in bold. These four inner-models (Figure 4.6) show that each warning message can significantly prompt a more intense and valid avoidance response. The direct impacts from reaction time and avoidance response on collision occurrence are significant across all four models. The non-speech, Danger and Directional warning would significantly impact drivers' eye movements including reducing TFF and prompting response before detecting the RLR vehicle. Given one of these three warnings, drivers' eye movements would significantly affect their reaction time and avoidance response, and the training would also have a significant influence on drivers' eye movements. Though the direct effect on eye movements (TFF) was not significant, the Braking warning can reduce reaction time directly and the training can further help shorten reaction time significantly with this warning was presented.

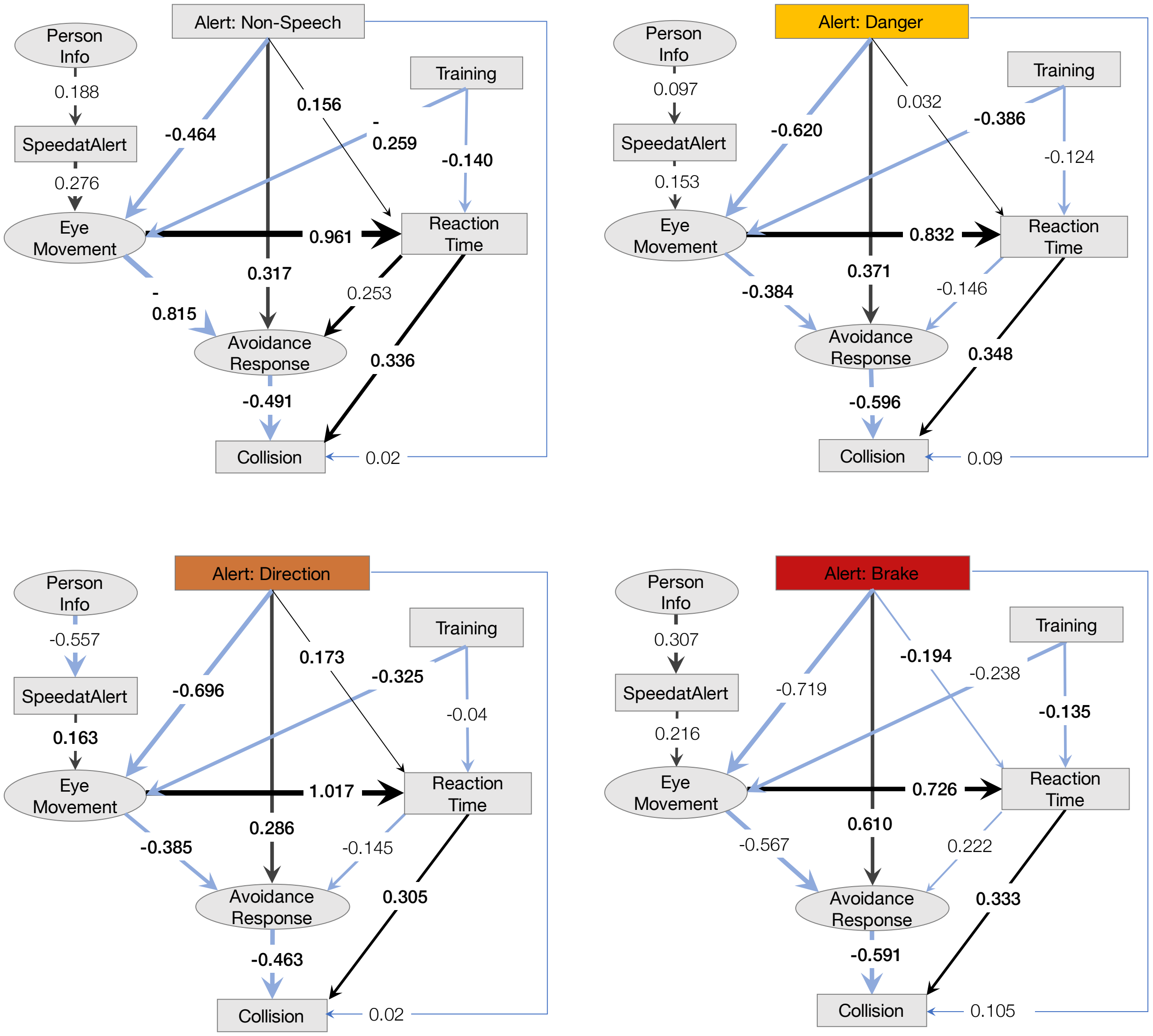


Figure 4.6: PLS Path Models (inner-models) for Each IMA Warning

Similar as the FCW study, the total effect was calculated based on the path coefficients from each model to better evaluate these IMA warnings. Based on Figure 4.7, the Brake warning was best in decreasing reaction time, prompting more appropriate avoidance responses and preventing collision occurrence. But it had the poorest performance in identifying the RLR vehicle. The Directional warning performed best in hazard (RLR vehicle) detection. Compared to all the speech-based warnings, the non-speech warning performed worst in reducing reaction time, TFF and the likelihood of having a collision.

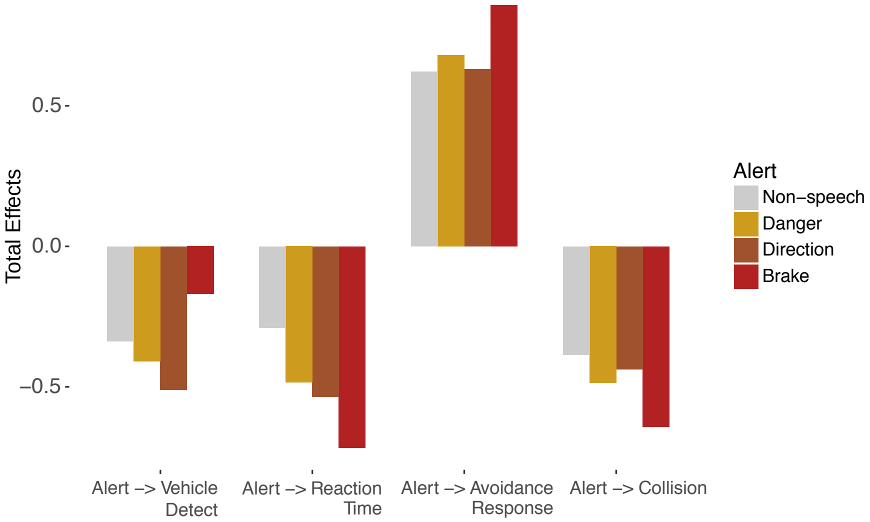


Figure 4.7: Total Effects: Direct + Indirect Effects for Each IMA Warning

## *4.4 Goodness of Fit for PLS Path Models*

A global criterion of goodness of fit (GoF) index for PLS has been proposed by Tenenhaus et al. (2004). This GoF takes into account the model quality at both the inner and the outer models and provide a single measure for the overall prediction performance. The GoF is calculated as the geometric mean of the average of all squared loadings of indicators (the average Communality) and the average R-squared of endogenous latent variables (the average $R^2$) (Tenenhaus et al., 2005):

$$GoF = \sqrt{\text{average Communality} \times \text{average } R^2} \quad (1)$$

As observed in Table 4.3 and 4.4, all FCW models have GoF values that are close to 0.5 and all IMA models have GoF values over 0.5, indicative of an acceptable fit (Wetzels et al., 2009).

Table 4.3: Goodness of fit for FCW PLS path model

| | FCW Models | | | | | |
|---|---|---|---|---|---|---|
| | All Alerts | D,F - M | D - L | D - H | F - L | F - H |
| Goodness of Fit (GoF) | 0.412 | 0.504 | 0.465 | 0.486 | 0.53 | 0.484 |

Table 4.4: Goodness of fit for IMA PLS path model

| | IMA Models | | | | |
|---|---|---|---|---|---|
| | All Alerts | Non-speech | Danger | Direction | Brake |
| Goodness of Fit (GoF) | 0.545 | 0.606 | 0.582 | 0.578 | 0.619 |

## *4.5 Discussion*

Most of the previous studies evaluated warning systems based on avoidance success and limited behavior measures such as brake reaction time and declaration rate (Curry et al., 2009; Lee et al., 2002). However, the avoidance process is very complex, and many factors determine the final avoidance success. Therefore, it is crucial to fully understand drivers' avoidance process, especially the causal relationships among warnings, avoidance behavior and collision occurrence when designing and evaluating a warning system. For scenarios with a latent hazard that cannot be easily detected, drivers' visual behaviors would also be very important and need to be completely comprehended. Considering the mechanisms of avoidance process are different, PLS path models with different structures were built separately for Study 1 (FCW) and 2 (IMA).

The findings suggest that the warning alerts have both direct and indirect impacts on final avoidance success for both FCW and IMA systems. The indirect effect on avoidance success was much stronger than the direct effect. PLS path models from these two studies show that drivers' reaction time affects their avoidance response (response intensity). In the IMA Study, drivers' reaction time and avoidance response were significantly affected by eye movements. The IMA PLS path models also incorporated the effects of training. In these two studies, some path coefficients were not significant because of the limited sample size within each warning condition.

Comparison across all tested FCW alerts based on the PLS path models show that D-L and F-H alerts performed worst in reducing reaction time, strengthening response intensity and promoting avoidance success. Hence, D-L is not recommended for a warning alert in such a critical situation. According to the data collected from the post-questionnaire, 47% drivers thought the intensity of this alert is too weak to catch their attention. The F-H alert is not recommended for FCW based on drivers' avoidance performance, despite these tones perceived as more urgent according to previous research(Edworthy et al., 1991; Hellier et al., 1993; Marshall et al., 2007). Participants' feedbacks revealed that F-H alert was considered too harsh and did not sound like a warning alert. Another interesting finding is that the performance of D, F-M alert in reducing collision was not as good as its performance in decreasing reaction time and strengthening response intensity. One possible is that drivers who swerved were more likely to successfully avoid the collision in this scenario.

The IMA PLS models showed the Brake warning was most effective in reducing reaction time, prompting appropriate avoidance response and enhancing avoidance success. However, in our current study, the tested RLR scenario was relatively straightforward, with perfect conditions and the best option for avoiding the vehicle by braking. It would be essential to examine this IMA warning in the context of other complex intersection hazards. Besides, this type of command warning requires the warning algorithm can precisely determine the most appropriate action after perceiving information of the latent hazards, surrounding traffics and the driving environment. Moreover, the effectiveness of this command warning relies heavily on users' trust in the system: the driver needs to follow the action as the command warning suggests

The PLS path models revealed the Direction warning has the best performance in improving drivers' hazard detection ability. This was not able to be uncovered by looking only individual measure in Chapter 3. Additionally, the path model results also indicate that the speech-base IMA warnings generally performed better than the non-speech one.

## Chapter 5

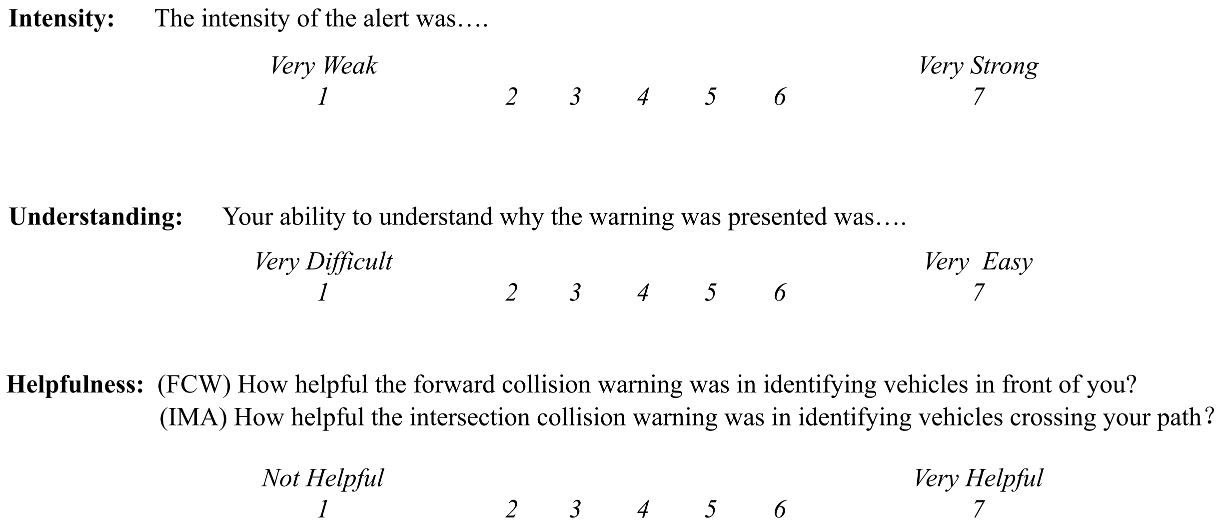
# SUBJECTIVE RATING OF WARNING EFFECTIVENESS

This chapter examines drivers' subjective ratings of presented warnings and investigates the relationships between subjective ratings and avoidance performance. It was hypothesized that drivers' subjective ratings would positively correlated to their avoidance performance. Other factors such as drivers' demographic characteristics and training would also impact their ratings and perceptions towards CWSs.

### *5.1 Subjective Rating of Warnings*

At the end of test drive (both experiment 1 and 2), each driver was requested to fill out an end questionnaire in which they were asked to rate the warning alert presented during the test drive. Specifically, they were asked to rate the presented warning from *"Intensity"*, *"Understanding"* and *"Helpfulness"*. All the questions were collected on a scale from 1-7, generally with 1 being very negative to 7 being very positive. The questions and the ranges of responses for each question were listed in Figure 5.1.

The subjective ratings for FCWs and IMA warnings are shown in Figure 5.2 and Figure 5.3. For most tested warnings in this dissertation, over 50% of the participants considered themselves can easily interpret the information presented by the warning (rating score above 4) and thought the warning somewhat or very helpful (rating score above 4). Among the



**Intensity:** The intensity of the alert was….

*Very Weak* *Very Strong*
*1 2 3 4 5 6 7*

**Understanding:** Your ability to understand why the warning was presented was….

*Very Difficult* *Very Easy*
*1 2 3 4 5 6 7*

**Helpfulness:** (FCW) How helpful the forward collision warning was in identifying vehicles in front of you?
(IMA) How helpful the intersection collision warning was in identifying vehicles crossing your path?

*Not Helpful* *Very Helpful*
*1 2 3 4 5 6 7*

Figure 5.1: Warning Alert Post Drive Subjective Rating Questionnaire

tested FCWs, D-L was considered with lowest intensity (47% of the participants rated it somewhat or very weak in intensity) and it was also considered not helpful (47%). The F-L warning was considered more difficult to be understood compared to the other three tonal warnings. This is highly consistent with findings based on drivers' avoidance behavior. Among the presented IMA warnings, the non-speech warning received higher ratings in intensity than all the speech warnings. The Brake warning was considered easy to be understood and most helpful, although its average rating score in intensity was not high. Similar conclusions were drawn based on drivers' avoidance performance. Surprisingly, the Direction warning that provided directional information of the RLR vehicle was considered difficult to be interpreted and less helpful than the other warnings. According to the feed-backs from participants, some of them felt confused about the directional information and thought it

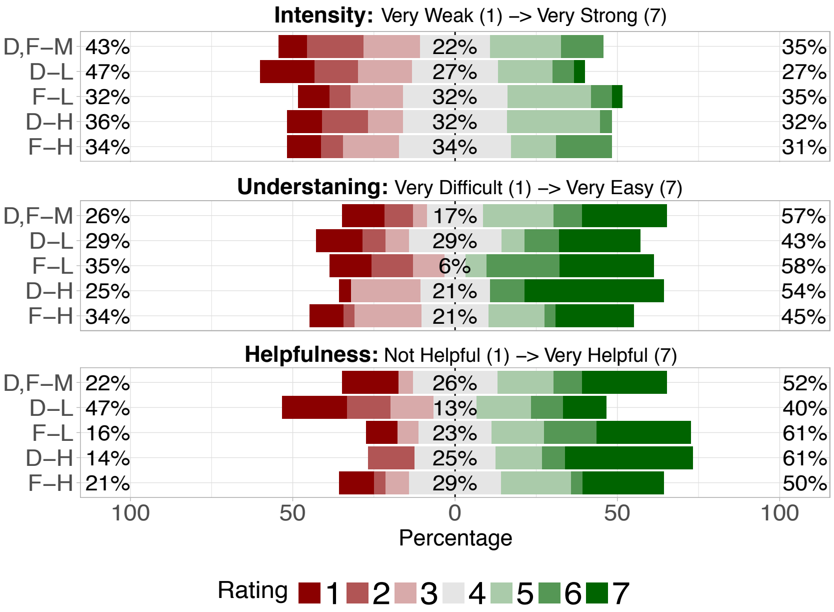


Figure 5.2: Subjective Ratings of FCWs

meant there was a vehicle traveling in the same direction on the left rather than a vehicle crossing their path on the left.

## *5.2 Correlation with Avoidance Performance*

### *5.2.1 Collision Involvement & Collision Velocity*

The collision involvement, to some extent, is the most intuitive and measurable result for users, which may have strong correlations with their feeling, understanding and evaluation of the warning system. From Figure 5.4, it can be observed that drivers who successfully avoided the rear-end collision have higher ratings in Intensity, Understanding and Helpfulness of FCWs. Due to the subjective ratings being a Likert scale, which is discrete, ordinal, and limited in the range from 1 to 7. A Mann-Whitney U test was performed to examine

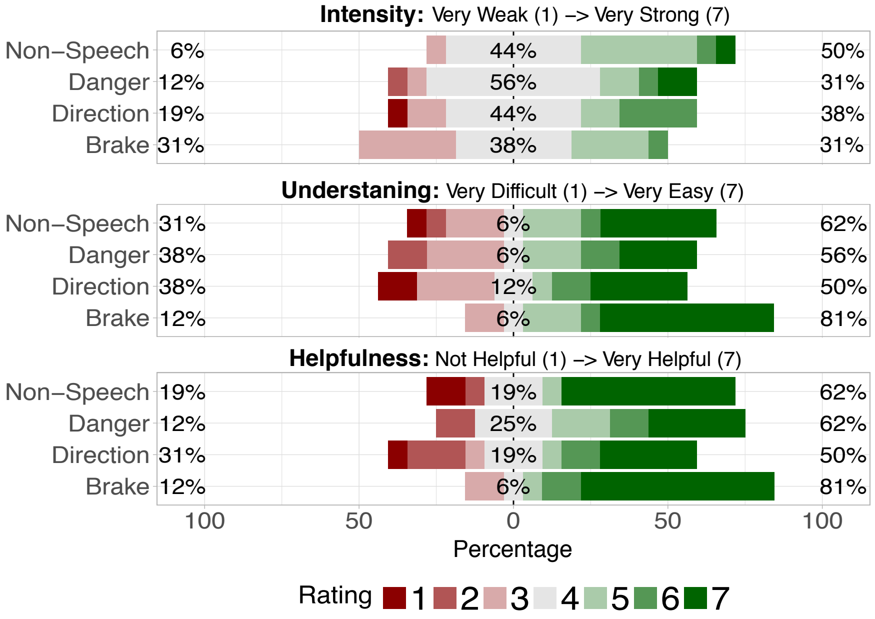


Figure 5.3: Subjective Ratings of IMA Warnings

the relationship between the collision involvement and drivers' subjective ratings. The result shows that drivers' rating of FCW in Helpfulness ($W = 2543, p = 0.002$) has a significant correlation with whether the driver avoided the collision. But, the correlation between collision involvement and ratings in FCW Intensity ($W = 2052, p = 0.54$) or FCW Understanding ($W = 2052, p = 0.54$) was not significant.

For IMA warnings, drivers' subjective ratings of Understanding ($W = 698, p < 0.001$) and Helpfulness ($W = 726.5, p < 0.001$) are also significantly correlated with collision involvement. Drivers who collided with the RLR vehicle showed poorer understandings of the presented IMA warning and had lower satisfaction with Helpfulness of these warnings (Figure 5.4). However, no significant difference was identified in the ratings of warning intensity

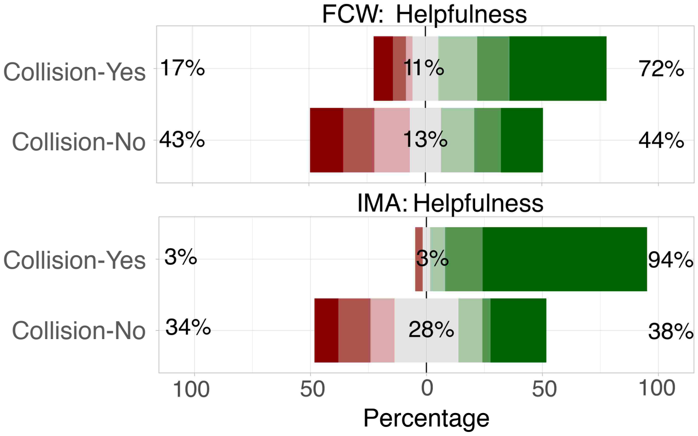


Figure 5.4: Subjective Ratings vs. Collision Involvement

between collision-involved drivers and drivers who avoided the intersection collision.

Among those crashed divers, their collision velocity was examined in the FCW study. However, no significant correlation was detected between driver's collision velocity and their subjective ratings of FCWs. Based on Figure 5.5, there is no clear trend between collision velocity and drivers' rating in Intensity, Understanding or Helpfulness of presented FCWs, indicating drivers' attitudes towards warnings may not affected by the collision severity once a collision happened.

### *5.2.2 Avoidance Behavior*

It has been demonstrated that drivers' subjective ratings have a positive correlation with avoidance success. However, after applying Pearson's correlation tests, it is surprising to find drivers' subjective evaluations were not correlated to their avoidance behavior, if controlling the impacts of collision involvement. That is among those collision-involved drivers(or

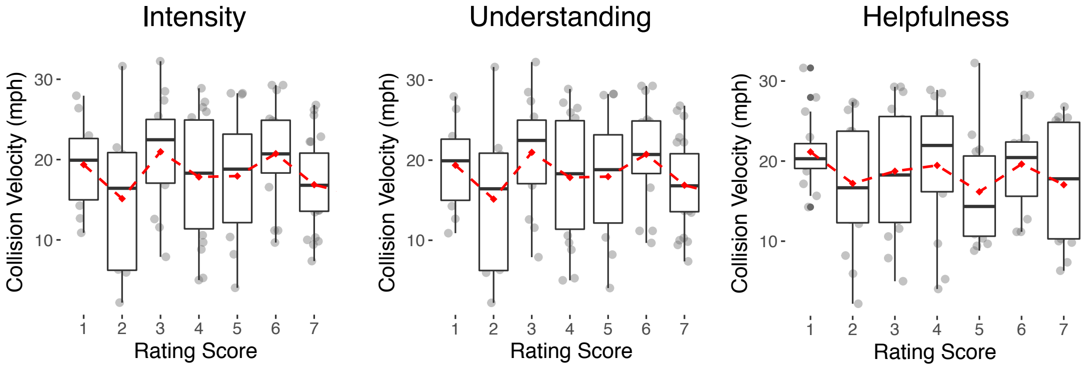


Figure 5.5: Subjective Ratings vs. Collision Velocity (red lines indicate mean values)

drivers who avoided the collision), no significant correlation was detected between drivers' eye movements (i.e. TFF) or avoidance behavior (i.e. TRRT, BRT, MaxLD, SpeedChange and MaxDecel) with their ratings in Intensity, Understanding and Helpfulness for both FCWs and IMA warnings.

## *5.3 Correlation with Driver Attributes*

In addition to the presented warning and collision involvement, some driver attributes may also lead to differences in attitudes and perceptions towards the presented warning and CWSs.

### *5.3.1 Demographic Factors*

Drivers' subjective evaluation of FCW system differed by gender. From Figure 5.6, male drivers, regardless of whether avoided the collision, have a average higher satisfaction in Helpfulness of FCWs. Though successfully avoided the collision, nearly 25% of these female drivers considered the system very unhelpful and rated it negative (rating score $<= 2$). However, no gender difference was detected in drivers' rating in Intensity and Understanding of FCWs.

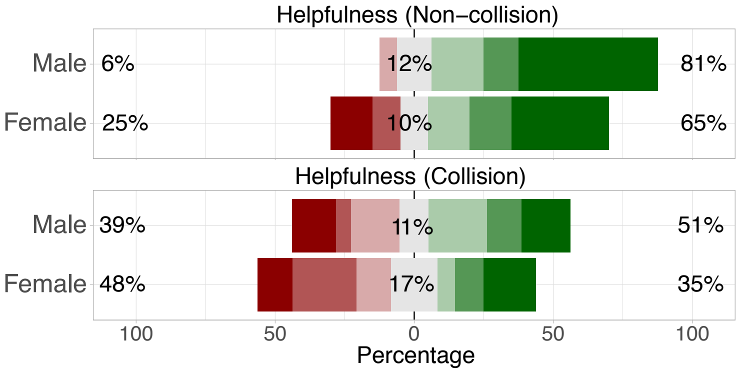


Figure 5.6: Gender Difference in Helpfulness of FCWs

For IMA warnings, no significant difference can be identified by gender. However, Mann-Whitney U test results uncover that age would lead a significant difference in drivers' understanding of IMA warnings ($W = 587, p = 0.036$). Figure 5.7 shows that elder drivers had a better understanding of information presented by the warning than younger drivers.

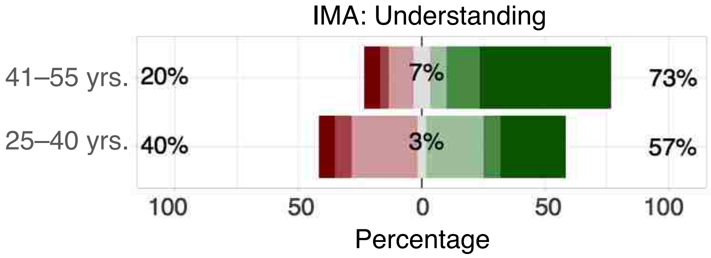


Figure 5.7: Age difference in Understanding of IMA Warnings

### *5.3.2 Training of CWSs*

In Chapter 3, the training of CWSs showed associations with avoidance success which was also correlated with higher ratings in Understanding and Helpfulness of IMA warnings. However, among the drivers who collided with the RLR vehicle, their average ratings of Helpfulness tended to be higher if training was received before test(Figure 5.8).

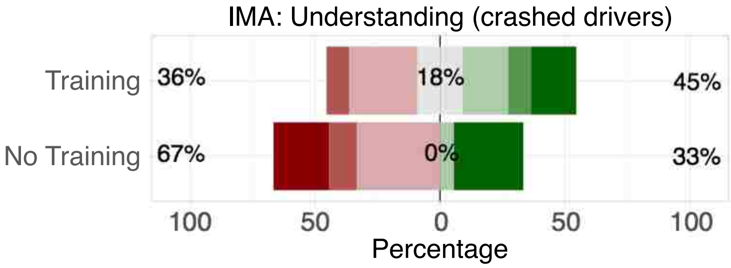


Figure 5.8: Training difference in Understanding of IMA Warnings among Crashed Drivers

## *5.4 Chapter Summary*

Based on questionnaire data from two studies, this chapter aimed to investigate drivers' subjective ratings of the warnings and understand the relationship between drivers' rating and their avoidance performance. All drivers rated the warning from the perspectives of Intensity, Understanding and Helpfulness. Their rating results suggest that drivers' subjective evaluations of the warning were generally consistent with results based on avoidance performance. The Direction warning was considered the least helpful for IMA scenario, which was slightly different from findings based on avoidance performance. Similar findings were demonstrated in previous ICWS studies, that a directional warning is no better than an unidirectional warning and can be even worse (Chang et al., 2009; Xiang et al., 2016). This is because the directional speech information appeared to create confusion for some drivers, which may have inadvertently created a distraction for them.

As expected, drivers' subjective ratings of the warning have a strong correlation with whether they avoided the collision during the test drive. However, if controlling the impacts of collision-involvement, no significant correlation was found between ratings and avoidance behavior including measures of reaction time and response intensity. That is, though avoidance performance was improved (i.e., shorter reaction time and greater speed reduction) when the warning was presented, drivers may still rate the warning system negatively as long as the collision happened. This indicates that drivers' assessment of warnings is more determined by the success of avoidance. This finding also suggests that drivers may fail to recognize the effectiveness of CWSs, that is their avoidance performance was enhanced and the severity of the collision was actually reduced.

Gender difference was identified in ratings of FCW. Male drivers tended to have higher satisfactions of FCW than female drivers. Previous studies found that females were more likely to trust and comply with FCWs than male drivers (Montgomery et al., 2014). As a result, female drivers may have a higher expectation of FCW and a lower tolerant attitude towards FCW than male driver. Additionally, elder drivers with more driving experience were found to have better understanding (self-rated) of presented IMA warnings than younger drivers. Moreover, for drivers who crashed in IMA study, the training was proved to contribute to a better understanding of presented warnings.

## Chapter 6

# GENERAL CONCLUSIONS

This chapter summarizes the overall findings of the dissertation, discusses the contributions of the results to the research field and publications, addresses study limitations, and presents future research topics that relate to the research aims.

### *6.1 Overall Summary*

The overall objective of this dissertation is to examine the effectiveness of the auditory collision warnings given different scenarios and understand the causal relationships between the warning, collision avoidance behavior, and the collision abatement. Five monotonous FCW alerts were generated from two different acoustic characteristics at three urgency levels for a rear-end pre-collision scenario; one monotonous and three speech-based IMA warnings with different verbal messages were created for a RLR scenario. These warning alerts were examined based on collision abatement and avoidance behavior. It was hypothesized that drivers' avoidance behavior and ability to avoid a collision would differ given the urgency level of a warning and information provided in a warning. It was also hypothesized that the causal relationship between the warning, avoidance behavior, and collision abatement would also differ given collision scenario with apparent and latent hazard. Two driving simulator studies were conducted for this purpose, and the key findings are summarized as follow.

1. Drivers' avoidance process is complex and the final avoidance success is determined by numerous factors. In both FCW and IMA studies, the auditory warning information has both direct and indirect effects on the occurrence of collisions, with the indirect impact playing a more critical role than the direct impact.

2. In the rear-end scenario with an apparent hazard, the monotonous FCW alerts can effectively bring drivers' attention back, generate shorter reaction times, strengthen response intensity (i.e., combined response, larger MaxDecel, and MaxLD) and reduce the likelihood of having a collision. The alert tones with a low urgency level of duty cycle or high urgency level of fundamental frequency were not recommended for FCW.

3. The FCW alerts have a direct impact on drivers' reaction time and response intensity. Also, the reaction time affects drivers' intensity of responses, indicating that quicker reaction would lead to more intense responses such as braking and steering simultaneously, larger maximum brake pedal force or a greater lane deviation.

4. In the RLR scenario with a latent hazard, both non-speech and speech IMA warnings can effectively assist drivers to avoid a potential intersection collision. However, the speech warnings generally have better performances than the monotonous one. Among all presented speech IMA warnings, the command warning "Brake now!", had the lowest collision rate and performed best in reducing reaction time and encouraging drivers to take the most appropriate action. However, that is not always the case and it is important to examine this alert for more complex situations. This kind of warning

command could lead to unintended unsafe consequences, because there is potential for the suggested action to be incorrect in some particular contexts (Lee et al., 2007)

5. In the RLR scenario, drivers' eye movements also differ given different warning information. The IMA warnings have a direct impact on eye movements including fixation pattern and TFF. Additionally, drivers' eye movements significantly impact their reaction time and avoidance response, i.e. speed change and maximum declaration.

6. The training of CWSs can significantly enhance drivers' visual and avoidance performance including smaller TFF, shorter reaction time and more appropriate responses to IMA warnings.

7. Drivers' subjective evaluation of CWs is strongly correlated with whether they successfully avoid the collision, but not correlated with any specific avoidance behavior. In addition, drivers' gender and age were significantly associated with their perceptions and attitudes towards CWSs.

## *6.2 Theoretical Implications*

Auditory CWSs that are widely used in modern passenger vehicles provide poor user experiences and limited effectiveness as they frequently fail to catch driver's attention and convey the correct information to drivers. However, there is no uniform technical standards and evaluating criterion to design and implement the in-vehicle auditory warning systems. This research attempted to examine the effects of auditory warning characteristics on drivers avoidance performance. The FCW study showed that drivers may have relatively poorer avoidance performance i.e. slower reaction time and less valid responses if the warning was presented with a range of low duty cycle or high fundamental frequency. A warning with high urgency level does not necessarily correspond to more valid or timely avoidance response, but can negatively startle users and generate other negative outcomes. The IMA study showed that speech warnings (when compared with non-speech warnings) are more appropriate for a scenario where the threat cannot be easily detected. The speech warning can assist to identify the hidden hazard and lead to better avoidance performances.

Evaluating the effectiveness of different auditory collision warnings can provide insights on how to improve the system design and safety performance. Prior studies have examined the effectiveness of CWSs based on a drivers' involvement in collision and limited behavior measures such as brake reaction time. However, driver's avoidance procedure is a complex multi-step process with different behaviors interacting with each other. Hence, examining only individual performance measures without also understanding the process, does not reveal the true effects of the alerts. This dissertation refines drivers' avoidance performance by analyzing multiple performance metrics (collision involvement, reaction time, response intensity), which allows for more comprehensive guidance for the design of CWSs that are effective. This dissertation also demonstrates the use of PLS path models for identifying the causal relationships across each stage of the avoidance process. This framework helps provide insights on the driver's avoidance behavior when using CWSs and also helps identify the impact of different processes on avoidance success.

## *6.3 Contributions & Publications*

Rear-end collisions are among the most common of vehicle-related accidents, which represents over 30% of all police-reported crashes (Cicchino, 2017). FCWS can effectively draw a driver's attention to critical roadway incidents and has the potential to reduce both the severity and occurrence rate of rear-end collisions. In 2015, over 50% of vehicles included front crash protection, and more automakers are making FCW available in new cars. However, a unified standard for designing and implementing the warning alert for these systems still does not exist. Also, few studies were found investigating the causal relationship between warning acoustic characteristics and collision avoidance behavior. By using the PLS path modeling, the study illustrated the causal relationship among FCW, avoidance behavior and occurrence of a collision. Study outcomes showed the auditory FCWs have both a direct and indirect effect on collision occurrence, with the indirect effect playing a more critical role on collision avoidance than the direct effect. The findings also suggested that the low urgency level of duty cycle and the high urgency level of fundamental frequency should be avoided in FCW. This work has been published in *Transportation Research Part F* (Wu et al., 2018).

Understanding drivers' avoidance strategies i.e., the tendency to brake or swerve is essential for the design and effectiveness of CWSs. Based on the data from the FCW experiment in this study, two driver avoidance maneuvers were identified: braking only and combined braking and steering. Log-linear analysis was used to investigate the likelihood of an avoidance maneuver given the driver characteristics (age, gender) and study location. Findings showed that drivers aged 40 years and older were more likely to use a combined braking and steering maneuver to avoid a rear-end collision. Drivers from urban areas were less likely to choose to brake only in response to FCW alerts. Younger drivers and drivers that live in more rural areas were more likely to select braking only to avoid a crash, which could be due to their experience in the less congested traffic environment. The findings of this study provide some insights into the factors associated with various avoidance strategies among drivers. This work has been published in the *Proceedings of the Human Factors and Ergonomics Society 61st Annual Meeting* (Wu et al., 2017).

Participants recruited for driving simulator studies may need to be excluded if they fail to complete the study as designed. The data that is analyzed therefore includes a sampling bias that is not typically considered but important to recognize. In this FCW study, a distracting task is part of the study protocol to divert drivers' attention away from the braking lights of the forward vehicle. In this experiment, two groups of participants became ineligible for further data analysis: (1) conservative drivers who had difficulty being artificially distracted and (2) risky drivers who did not maintain vehicle control while distracted. Two separate binary logit models were used to identify factors associated with these two driver types. As age increased, drivers were more likely to be in one of these driver types and are, therefore, likely to be disqualified from further examination. Females had a higher likelihood of losing control during the distraction task when compared to males. Further, drivers with previous driving simulator experience were better able to maintain vehicle control while distracted. This work has been published in the *Proceedings of the Human Factors and Ergonomics*

*Society 59st Annual Meeting* (Wu et al., 2015).

Intersection-related crashes have accounted for more than 40% of all crashes and 20% of all fatal crashes in the US, second only to rear-end crashes (Cunard et al., 2004). An IMA system can detect latent hazards and warn drivers when it is unsafe to enter an intersection. Although speech or verbal message is a promising way to convey warning information to drivers especially in the scenarios where hazards cannot be easily detected, the effects of different information carried by the IMA warning remains unknown. Various statistical methods i.e., ANOVA, logistic model, multivariate model, and log-linear analysis were applied to investigate the effects of warning message on driving behavior and eye movements. The effects of training were also examined. The study outcomes showed that all presented IMA warnings can effectively enhance driver's avoidance performance and assist them in avoiding a collision. Significant differences were observed in collision occurrence, avoidance behavior and eye movements and the effects of training also differed given different warning messages. The results also suggested that the command IMA warning performed best and the training has a potential to enhance the effectiveness of CWs. The findings related to the IMA Study in Chapter 3 have been submitted to the *Journal of Human Factors and Ergonomics* (Wu and Boyle, submitted).

As a most advanced v2v-based CW, the research in the auditory IMA warnings need to be further explored. Drivers' behavior to avoid the collision in an IMA target scenario is very different from that in an traditional CWS scenario FCW and needs to be comprehensively understood. Since the hazard cannot be easily detected immediately after the IMA warning is issued in the scenario of Study 2, drivers' eye movements played an important role in drivers' avoidance process. However, few studies have focused on the relationships among IMA warning, eye movements, avoidance behavior, and collision abatement. A new PLS path model was constructed to investigate the causal relationships among these factors. The model showed that IMA warnings have a direct impact on drivers' eye movements, reaction time, avoidance response and collision occurrence. However, drivers' eye movements would also affect their reaction time and how they responded to the impending collision. A manuscript of findings related to IMA study using PLS path modeling in Chapter 4 is being prepared for submission to *Transportation Research Part F* (Wu and Boyle, in preparation).

## *6.4 Limitations*

### *6.4.1 Experimental Design*

Both of the studies designed for this dissertation used a between-subjects experimental design (one-treatment per subject) with each driver presented with only one warning alert and one collision event. This design was deemed necessary to capture drivers' most natural responses to a severe hazardous without any expectations or preparation of the pre-crash event. Hence, the sample size per warning alert is limited, especially for Study 2 with only 16 participants within each IMA warning, which impacts the statistical power.

In Study 1, two acoustic characteristics were examined with only three levels and the current level setting was not refined enough. Study 2 tested several speech-based IMA warnings including a general speech warning, a directional warning, and a command warning. The initial hypothesis was that directional warning would provide clues for drivers to better detect the RLR vehicle and guide the drivers' eyes toward the RLR vehicle more quickly than the general speech warning. Previous studies also proved that the directional speech warning using words front or back could effectively guide drivers' attention to some specific direction (Ho and Spence, 2005; Yan et al., 2014; Zhang et al., 2016). However, there were no significant differences between these two warning messages. The directional warning even obtained the lowest ratings based on drivers' subjective evaluation. One possible reason is that the warning content confused drivers. According to drivers' feedback, some of them thought it meant there was a vehicle traveling in the same direction on the left (similar to a blind spot warning) rather than a vehicle crossing their path on the left. Additionally, the Study 2 only tested the RLR scenario with violating vehicle coming from one direction (left). More RLR situations with RLR vehicle violating from different directions need to be examined for accurately assessing the effectiveness of directional warnings. In addition, there may exist cognitive heterogeneity within warnings. All subjects may process the warning "Brake now" in similar ways (all the participants are native speakers), but the cognitive burden of hearing and handling directional information may vary across subjects.

### *6.4.2 Data Collection*

Driving simulator studies can introduce sampling bias during the data collection process. In study 1, drivers who failed in the last distraction task (either looked back too early or steered out of their driving lane) were excluded from further data analysis. Also, participants were screened given whether they had distracting driving experience and two candidates were ineligible due to this reason. Both of these may bring sampling bias in FCW study.

In study 2, 80 participants completed the test drive and all of them are balanced in gender and age. But the participants in this study may not be representative in general because they were all from Seattle area.

Moreover, we noticed that a large majority of participants in both studies have limited experience in using CWSs or advanced driving assist systems (ADASs). This may lead to an underestimation of the effectiveness of presented warnings since drivers' familiarization have substantial impacts on their understanding and interaction with an in-vehicle system.

Response bias may also occur during the collection of questionnaire data. In the post-drive questionnaire, all questionnaires used rating scales to allow drivers to rate the presented warning. However, people may interpret and use scales differently. Some participants might be “extreme responders” who like to use the edges of the scales, whereas others may like to focus their responses around the midpoints while rarely using the extreme outer points. Gender and age differences in subjective evaluation of warnings may also be associated with the heterogeneity in self-reporting.

### *6.4.3 Analytical Modeling*

The current analysis considered the avoidance process from a holistic perspective but included only a few key indicators, i.e., reaction time and reaction intensity were observed concerning avoidance behavior. We recognize that drivers’ response sequence is a complex interaction and assessing their response is a difficult task. Generally, drivers’ avoidance is comprised of several stages including the perception of hazards, decide response action and finally execute maneuvers. Most indicators examined in this study are focused on the latter two steps. More indicators measuring the perception of hazards need to be investigated for a more comprehensive description of the whole avoidance process. Since drivers would adjust their maneuvers based on their understanding of dangers, the relationship between hazard perception, decision on actions and maneuver execution also need to be identified in PLS path models.

PLS path models assume a linear association among latent variables and our initial assessment shows that this association is reasonable. However, we do recognize that there may exist some nonlinear relationships among warning alerts, avoidance behavior, and collision occurrence, and this will need to be further explored with additional data sets. In Chapter 4, the total effects (sum of direct and indirect impact) of each warning was calculated based on the path coefficients. However, due to the limited sample size, some of the path coefficients were not statistically significant, leading to biases in interpreting the total effects of the presented warnings.

The current structure of the PLS path models were established based on very limited background knowledge and previous literature. However, further exploration need is very necessary to get stronger theoretical support especially how to establish the causal directions between constructs.

There are also limitations to the practicality and implications of the study results. Study 2 revealed that the command IMA warning “Brake now” generally performed best in avoiding the potential collision. However, its command-like nature could become a problem in the litigation process. In the current stage, the warning suggesting drivers with any actions are generally avoided by automobile manufacturers (Lee et al., 2007). This is because the automobile manufacturers would be considered liable for the consequences if the driver performed the suggested actions that may be inappropriate under some particular contexts. For example, in the tested RLR scenario, a driver braked hard after following the Brake warning but rear-ended by the following vehicle. This situation may lead to disputes between drivers and automobile manufacturers.

## *6.5 Future Research*

Since expectancy was found to have the most significant impact on drivers' avoidance behavior for surprising situations, A between-subjects design was used to capture drivers' most natural response and avoid them being "too prepared" to respond. Future experiments could consider a within-subject design with multiple collision events or multiple warnings for each driver. Moreover, the learning effects can be reduced by counterbalancing the order and other statistical techniques such as mixed models could be used to account for the within-subject correlation of the repeated measures data. However, the experiment would need to be carefully designed to minimize the impacts of expectancy.

Study 1 tested all the monotonous warnings only within a leading vehicle decelerating scenario. Also, Study 2 only examined the RLR scenario with violation vehicle in one direction. However, drivers' avoidance behavior would change with different situations of obstacles or conflicting trajectories. In addition, Study 1 only focused on the setting of single acoustic characteristic. Each warning tone is comprised of numerous components and the combination of different acoustic features may impact the warning performance. Future FCW studies should test more acoustic characteristics with more refined urgency levels as well as the combination of these characteristics, which can provide more guidelines for designing the system. Future studies also need to examine different rear-end and intersection pre-collision scenarios to make sure that the results have a better generalization capability.

These two studies currently focused on investigating the causal relationships between the warning, avoidance behavior, and collision abatement. However, the reduction in collision severity is another important indicator to assess the effectiveness of CWSs. The current PLS path models were explicitly tuned to include the presented response variables (collision occurrence) only and not suitable for addressing the severity of a collision, which is probably a categorical variable. Future studies could consider collecting more variables and creating additional PLS path models to provide insights into collision severity using a measure such as collision velocity.

The current study has proved that drivers' familiarity (training) to the system has significant impacts on drivers' avoidance performance and is strongly associated with the effectiveness of the system. However, this topic needs further investigation in future researches. We also found very few participants who enrolled in this study had much experience using CWSs. Requirements about the experience in CWSs or ADASs need to be applied for screening particiapants during recruitment.

# BIBLIOGRAPHY

Abe, G. and Richardson, J. (2006). Alarm timing, trust and driver expectation for forward collision warning systems. *Applied ergonomics*, 37(5):577–586.

Administration, N. H. T. S. et al. (2013). Preliminary statement of policy concerning automated vehicles. *Washington, DC*, pages 1–14.

Algina, J. and Olejnik, S. F. (1984). Implementing the welch-james procedure with factorial designs. *Educational and Psychological Measurement*, 44(1):39–48.

Anstey, K. J., Wood, J., Lord, S., and Walker, J. G. (2005). Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical psychology review*, 25(1):45–65.

Bakowski, D. L., Davis, S. T., and Moroney, W. F. (2015). Reaction time and glance behavior of visually distracted drivers to an imminent forward collision as a function of training, auditory warning, and gender. *Procedia Manufacturing*, 3:3238 – 3245.

Baldwin, C. L. and Lewis, B. A. (2014). Perceived urgency mapping across modalities within a driving context. *Applied Ergonomics*, 45(5):1270 – 1277.

Baldwin, C. L. and Moore, C. (2002). Perceived urgency, alerting effectiveness and annoyance of verbal collision avoidance system messages. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 46, pages 1848–1852.

Balk, S. A. (2014). Assessing driver reactions to two collision warning systems-findings from a simulation experiment. *Institute of Transportation Engineers. ITE Journal*, 84(8):33.

Baumann, M., Keinath, A., Krems, J. F., and Bengler, K. (2004). Evaluation of in-vehicle HMI using occlusion techniques: experimental results and practical implications. *Applied Ergonomics*, 35(3):197 – 205.

Bella, F. and Silvestri, M. (2017). Effects of directional auditory and visual warnings at intersections on reaction times and speed reduction times. *Transportation research part F: traffic psychology and behaviour*, 51:88–102.

Blumenthal, T. D. (1996). Inhibition of the human startle response is affected by both prepulse intensity and eliciting stimulus intensity. *Biological Psychology*, 44(2):85 – 104.

Brown, T. L., Lee, J. D., and McGehee, D. V. (2001). Human performance models and rear-end collision avoidance algorithms. *Human Factors*, 43(3):462–482.

Burt, J. L., Bartolome, D. S., Burdette, D. W., and Comstock, J. R. (1995). A psychophysiological evaluation of the perceived urgency of auditory warning signals. *Ergonomics*, 38(11):2327 – 2340.

Cahour, B. and Forzy, J.-F. (2009). Does projection into use improve trust and exploration? an example with a cruise control system. *Safety science*, 47(9):1260–1270.

Chang, S.-H., Lin, C.-Y., Fung, C.-P., Hwang, J.-R., and Doong, J.-L. (2008). Driving performance assessment: effects of traffic accident location and alarm content. *Accident Analysis & Prevention*, 40(5):1637–1643.

Chang, S.-H., Lin, C.-Y., Hsu, C.-C., Fung, C.-P., and Hwang, J.-R. (2009). The effect of a collision warning system on the driving performance of young drivers at intersections. *Transportation Research Part F: Traffic Psychology and Behaviour*, 12(5):371 – 380.

Cicchino, J. B. (2017). Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accident Analysis and Prevention*, 99:142 – 152.

Cobb, B. R., Rumí, R., and Salmerón, A. (2007). Bayesian network models with discrete and continuous variables. In *Advances in probabilistic graphical models*, pages 81–102. Springer.

Cunard, R. A., Davis, G. W., Demosthenes, P., et al. (2004). Intersection safety issue briefs. *Washington, DC: ITE (Institute of Traffic Engineers, US)/FHWA (Federal Highway Administration, US) Publication*, pages 20–22.

Curry, R., Blommer, M., Greenberg, J., and Tijerina, L. (2009). Immediate recall of driver warnings in forward collision warning scenarios. *Transportation Research Record: Journal of the Transportation Research Board*, 2138:28 – 33.

D'Ambrosio, L. A., Donorfio, L. K., Coughlin, J. F., Mohyde, M., and Meyer, J. (2008).

Gender differences in self-regulation patterns and attitudes toward driving among older adults. *Journal of Women & Aging*, 20(3-4):265–282.

Deery, H. A. (1999). Hazard and risk perception among young novice drivers. *Journal of safety research*, 30(4):225–236.

Dey, K. C., Rayamajhi, A., Chowdhury, M., Bhavsar, P., and Martin, J. (2016). Vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communication in a heterogeneous wireless network–performance evaluation. *Transportation Research Part C: Emerging Technologies*, 68:168–184.

Dotzauer, M., Caljouw, S. R., de Waard, D., and Brouwer, W. H. (2013). Intersection assistance: A safe solution for older drivers? *Accident Analysis & Prevention*, 59:522–528.

Edworthy, J. and Adams, A. S. (1996). *Warning design: A research prospective.* Taylor & Francis.

Edworthy, J., Hellier, E., Walters, K., Weedon, B., and Adams, A. (2000). The relationship between task performance, reaction time, and perceived urgency in nonverbal auditory warnings. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 44(22):674 – 677.

Edworthy, J., Loxley, S., and Dennis, I. (1991). Improving auditory warning design: Relationship between warning sound parameters and perceived urgency. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 33(2):205 – 231.

Elvik, R. (2013). A re-parameterisation of the power model of the relationship between the speed of traffic and the number of accidents and accident victims. *Accident Analysis & Prevention*, 50:854–860.

Fornell, C. and Bookstein, F. L. (1982). Two structural equation models: LISREL and PLS applied to consumer exit-voice theory. *Journal of Marketing Research*, 19(4):440.

Graham, R. (1999). Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application. *Ergonomics*, 42(9):1233–1248.

Gray, R. (2011). Looming auditory collision warnings for driving. *Human factors*, 53(1):63–74.

Haas, E. and Edworthy, J. (2006). An introduction to auditory warnings and alarms. *Handbook of warnings*, pages 189–198.

Haas, E. C. and Casali, J. G. (1995). Perceived urgency of and response time to multi-tone and frequency-modulated warning signals in broadband noise. *Ergonomics*, 38(11):2313 – 2326.

Haas, E. C. and Erp, J. B. V. (2014). Multimodal warnings to enhance risk communication and safety. *Safety Science*, 61:29 – 35.

Hakamies-Blomqvist, L., Mynttinen, S., Backman, M., and Mikkonen, V. (1999). Age-related differences in driving: Are older drivers more serial? *International Journal of Behavioral Development*, 23(3):575–589.

Hanafi, M. (2007). PLS path modelling: computation of latent variables with the estimation mode b. *Computational Statistics*, 22(2):275 – 292.

Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., and Wang, J. (2014). Vehicle-to-vehicle communications: Readiness of v2v technology for application. Technical report.

Harms, L. (1991). Variation in drivers' cognitive load. effects of driving through village areas and rural junctions. *Ergonomics*, 34(2):151–160.

Hassan, H. M. and Abdel-Aty, M. A. (2011). Analysis of drivers behavior under reduced visibility conditions using a structural equation modeling approach. *Transportation Research Part F: Traffic Psychology and Behaviour*, 14(6):614 – 625.

Hellier, E. J., Edworthy, J., and Dennis, I. (1993). Improving auditory warning design: Quantifying and predicting the effects of different warning parameters on perceived urgency. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 35(4):693 – 706.

Helsey, A. (2015). There are about 1.7 million rear-end collisions on u.s. roads each year. heres how to stop them. *The Washington Post*.

Henseler, J. and Sarstedt, M. (2012). Goodness-of-fit indices for partial least squares path modeling. *Computational Statistics*, 28(2):565 – 580.

Ho, C. and Spence, C. (2005). Assessing the effectiveness of various auditory cues in capturing a driver's visual attention. *Journal of experimental psychology: Applied*, 11(3):157.

Jenness, J. W., Boyle, L. N., Lee, J. D., Chang, C.-C., Venkatraman, V., Gibson, M., Riegler, K. E., and Kellman, D. (2016). In-vehicle voice control interface performance evaluation. Technical report.

Jermakian, J. S. (2011). Crash avoidance potential of four passenger vehicle technologies. *Accident Analysis and Prevention*, 43(3):732 – 740.

JOHANSEN, S. (1980). The welch-james approximation to the distribution of the residual sum of squares in a weighted linear regression. *Biometrika*, 67(1):85–92.

Jurewicz, C., Sobhani, A., Woolley, J., Dutschke, J., and Corben, B. (2016). Exploration of vehicle impact speed–injury severity relationships for application in safer road design. *Transportation research procedia*, 14:4247–4256.

Kline, R. B. (2015). *Principles and practice of structural equation modeling.* Guilford publications.

Kloeden, C., McLean, A., Moore, V., and Ponte, G. (2001). *Travelling speed and the risk of crash involvement on rural roads, report CR 204.* Australian Transport Safety Bureau.

Kloeden, C. N., McLean, J., and Glonek, G. F. V. (2002). *Reanalysis of travelling speed and the risk of crash involvement in Adelaide South Australia.* Australian Transport Safety Bureau.

Koustanaï, A., Cavallo, V., Delhomme, P., and Mas, A. (2012). Simulator training with a forward collision warning system: Effects on driver-system interactions and driver trust. *Human factors*, 54(5):709–721.

Koustanai, A., Mas, A., Cavallo, V., and Delhomme, P. (2010). Familiarization with a forward collision warning on driving simulator: cost and benefit on driversystem interactions and trust.

Lauria, E. J. and Duchessi, P. J. (2007). A methodology for developing bayesian networks: An application to information technology (it) implementation. *European Journal of operational research*, 179(1):234–252.

Lee, J., McGehee, D., Brown, T., and Marshall, D. (2006). Effects of adaptive cruise control and alert modality on driver performance. *Transportation Research Record: Journal of the Transportation Research Board*, 1980:49 – 56.

Lee, J. D., McGehee, D. V., Brown, T. L., and Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 44(2):314 – 334.

Lee, S. E., Perez, M. A., Doerzaph, Z. R., Stone, S. R., Neale, V. L., Brown, S. B., Knipling, Ronald R.and Holbrook, G. T., and Dingus, T. A. (2007). Intersection collision avoidance-violation project: Final project report. *DOT HS 810 749*.

Lerner, N., Jenness, J., Robinson, E., Brown, T., Baldwin, C., and Llaneras, R. (2011). *Crash Warning Interface Metrics: Final Report*. National Highway Traffic Safety Administration (NHTSA), Department of Transportation (DOT), Washington, DC.

Lerner, N., Singer, Jeremiah Huey, R., Brown, T., Marshall, D., Chrysler, S., Schmitt, R., Baldwin, C. L., Eisert, J. L., Lewis, B., Bakker, A. I., and Chiang, D. P. (2015). *Driver-Vehicle Interfaces for Advanced Crash Warning Systems: Research on Evaluation Methods and Warning Signals*. National Highway Traffic Safety Administration (NHTSA), Department of Transportation (DOT), Washington, DC.

Lewis, B. A., Eisert, J. L., and Baldwin, C. L. (2017). Validation of essential acoustic parameters for highly urgent in-vehicle collision warnings. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 60(2):248 – 261.

Li, G., Zhou, Y., Bai, T., Lin, J., Pang, Y., Wu, W., Din, S., and Jeon, G. (2018). Performance analysis for low-complexity detection of mimo v2v communication systems. *Computer Networks*, 140:92–100.

Lombardi, D. A., Horrey, W. J., and Courtney, T. K. (2017). Age-related differences in fatal intersection crashes in the united states. *Accident Analysis & Prevention*, 99:20–29.

Lukuc, M. (2012). Light vehicle driver acceptance clinics preliminary results. *National Highway Traffic Safety Administration.*

Maccarini, A. R., Gucciardo, A. G., and Pieri, F. (2017). Faculty of 1000 evaluation for vocal age disguise: the role of fundamental frequency and speech rate and its perceived effects. *F1000 - Post-publication peer review of the biomedical literature*.

Marshall, D. C., Lee, J. D., and Austria, P. A. (2007). Alerts for in-vehicle information systems: Annoyance, urgency, and appropriateness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(1):145 – 157.

McCallum, M. (2006). Integrated vehicle-based safety system heavy truck driver vehicle interface (dvi) literature review.

McGehee, D., Brown, T., Lee, J., and Wilson, T. (2002). Effect of warning timing on collision avoidance behavior in a stationary lead vehicle scenario. *Transportation Research Record: Journal of the Transportation Research Board*, 1803:1 – 6.

McGehee, D. V., Mazzae, E. N., and Baldwin, G. S. (2000). Driver reaction time in crash avoidance research: validation of a driving simulator study on a test track. In *Proceedings of the human factors and ergonomics society annual meeting*, volume 44, pages 3–320. SAGE Publications Sage CA: Los Angeles, CA.

Misener, J. A. (2010). Cooperative intersection collision avoidance system (cicas): Signalized left turn assist and traffic signal adaptation. Technical report.

Mitchell, C. and Suen, S. (1997). Its impact on elderly drivers. In *XIIIth World meeting of the International Road FederationInternational Road Federation*.

Mohebbi, R., Gray, R., and Tan, H. Z. (2009). Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone. *Human Factors*, 51(1):102–110.

Monecke, A. and Leisch, F. (2012). semPLS: Structural equation modeling using partial least squares. *Journal of Statistical Software*, 48(3).

Montgomery, J., Kusano, K. D., and Gabler, H. C. (2014). Age and gender differences in time to collision at braking from the 100-car naturalistic driving study. *Traffic injury prevention*, 15(sup1):S15–S20.

Mueller, A. S. and Trick, L. M. (2012). Driving in fog: The effects of driving experience and visibility on speed compensation and hazard avoidance. *Accident Analysis & Prevention*, 48:472–479.

Najm, W., Smith, J. D., Smith, D. L., et al. (2001). Analysis of crossing path crashes. Technical report, John A. Volpe National Transportation Systems Center (US).

Najm, W. G., Ranganathan, R., Srinivasan, G., Smith, J. D., Toma, S., Swanson, E., Burgett, A., et al. (2013). Description of light-vehicle pre-crash scenarios for safety applications based on vehicle-to-vehicle communications. Technical report, United States. National Highway Traffic Safety Administration.

Najm, W. G., Smith, J. D., and Yanagisawa, M. (2007). Pre-crash scenario typology for crash avoidance research. In *DOT HS*. Citeseer.

Najm, W. G., Stearns, M. D., Howarth, H., Koopmann, J., and Hitz, J. (2006). *Evaluation* *of an Automotive Rear-End Collision Avoidance System.* National Highway Traffic Safety Administration (NHTSA), Department of Transportation (DOT), Washington, DC.

NHTSA (2007). *Analyses of Rear-End Crashes and Near-Crashes in the 100-Car Naturalistic Driving Study to Support Rear-Signaling Countermeasure Development.* National Highway Traffic Safety Administration (NHTSA), Department of Transportation (DOT), Washington, DC.

Oxley, P. and Mitchell, C. (1995). Final report on elderly and disabled drivers information telematics (project eddit). *Commission of the European Communities DG XIII, R & D Programme Telematics Systems in the Area of Transport (DRIVE II), Brussels, Belgium.*

Peng, Y. and Boyle, L. N. (2015). Driver's adaptive glance behavior to in-vehicle information systems. *Accident Analysis & Prevention*, 85:93–101.

Porter, M., Irani, P., and Mondor, T. (2008). Effect of auditory road safety alerts on brake response times of younger and older male drivers: A simulator study. *Transportation Research Record: Journal of the Transportation Research Board*, (2069):41–47.

Regan, M. A., Triggs, T. J., Young, K. L., Tomasevic, N., Mitsopoulos, E., Stephan, K., and Tingvall, C. (2006). On-road evaluation of intelligent speed adaptation, following distance warning and seatbelt reminder systems: Final results of the tag safecar project. *Monash University Accident Research Centre Reports*, 253:270.

Reimer, B., Mehler, B., Coughlin, J. F., Roy, N., and Dusek, J. A. (2011). The impact of a naturalistic hands-free cellular phone task on heart rate and simulated driving performance in two age groups. *Transportation research part F: traffic psychology and behaviour*, 14(1):13–25.

Richards, D., Cuerden, R., and Britain, G. (2009). *The relationship between speed and car driver injury severity*. Department for Transport London.

Rouse, M. (2014). Vehicle-to-vehicle communication (v2v communication). *Internet of Things Agenda*.

Ruscio, D., Ciceri, M. R., and Biassoni, F. (2015). How does a collision warning system shape driver's brake response time? the influence of expectancy and automation complacency on real-life emergency braking. *Accident Analysis & Prevention*, 77:72–81.

Sanchez, G. (2013). *PLS Path Modeling with R*.

Sengupta, R., Rezaei, S., Shladover, S. E., Cody, D., Dickey, S., and Krishnan, H. (2007). Cooperative collision warning systems: Concept definition and experimental implementation. *Journal of Intelligent Transportation Systems*, 11(3):143–155.

Shackman, J. D. (2013). The use of partial least squares path modeling and generalized structured component analysis in international business research: A literature review. *International Journal of Management*, 30(3):78.

Shaheen, S. A. and Niemeier, D. A. (2001). Integrating vehicle design and human factors:

minimizing elderly driving constraints. *Transportation Research Part C: Emerging Technologies*, 9(3):155–174.

Son, J., Lee, Y., and Kim, M.-H. (2011). Impact of traffic environment and cognitive workload on older drivers behavior in simulated driving. *International Journal of Precision Engineering and Manufacturing*, 12(1):135–141.

Son, J., Reimer, B., Mehler, B., Pohlmeyer, A., Godfrey, K., Orszulak, J., Long, J., Kim, M., Lee, Y., and Coughlin, J. F. (2010). Age and cross-cultural comparison of drivers cognitive workload and performance in simulated urban driving. *International Journal of Automotive Technology*, 11(4):533–539.

Spence, C. and Ho, C. (2008). Multisensory warning signals for event perception and safe driving. *Theoretical Issues in Ergonomics Science*, 9(6):523–554.

Spiegelman, C., Park, E. S., and Rilett, L. R. (2016). *Transportation statistics and microsimulation*. Chapman and Hall/CRC.

Sternlund, S., Strandroth, J., Rizzi, M., Lie, A., and Tingvall, C. (2017). The effectiveness of lane departure warning systemsa reduction in real-world passenger car injury crashes. *Traffic injury prevention*, 18(2):225–229.

Suetomi, T., Kido, K., Yamamoto, Y., and Hata, S. (1995). A study of collision warning system using a moving-base driving simulator. In *Proceedings of teh Intelligent Transportation System World Congress, At Yokohama, Japan.*

Tenenhaus, A. and Tenenhaus, M. (2011). Regularized generalized canonical correlation analysis. *Psychometrika*, 76(2):257 – 284.

Tenenhaus, M., Amato, S., and Vinzi, V. E. (2004). *XLII SIS Scientific Meeting*, volume 1, pages 739 – 742. CLEUP.

Tenenhaus, M., Vinzi, V. E., Chatelin, Y.-M., and Lauro, C. (2005). PLS path modeling. *Computational Statistics and Data Analysis*, 48(1):159 – 205.

Turner, C. and McClure, R. (2003). Age and gender differences in risk-taking behaviour as an explanation for high incidence of motor vehicle crashes as a driver in young males. *Injury control and safety promotion*, 10(3):123–130.

Underwood, G., Chapman, P., Bowden, K., and Crundall, D. (2002). Visual search while driving: skill and awareness during inspection of the scene. *Transportation Research Part F: Traffic Psychology and Behaviour*, 5(2):87–97.

Uno, H. and Hiramatsu, K. (2001). Collision avoidance capabilities of older drivers and improvement by warning presentations. In *Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles*.

Verbunt, M. and Bartneck, C. (2009). Sensing senses: Tactile feedback for the prevention of decubitus ulcers. *Applied Psychophysiology and Biofeedback*, 35(3):243 – 250.

Wege, C., Will, S., and Victor, T. (2013). Eye movement and brake reactions to real world brake-capacity forward collision warnings - a naturalistic driving study. *Accident Analysis and Prevention*, 58:259 – 270.

Werneke, J. and Vollrath, M. (2013). How to present collision warnings at intersections?a comparison of different approaches. *Accident analysis & prevention*, 52:91–99.

Wetzels, Schrder, O., and Oppen, V. (2009). Using PLS path modeling for assessing hierarchical construct models: Guidelines and empirical illustration. *MIS Quarterly*, 33(1):177.

Wiese, E. E. and Lee, J. D. (2004). Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance. *Ergonomics*, 47(9):965 – 986.

Wogalter, M. S. (2006). *Handbook of warnings.* Lawrence Erlbaum Associates.

Wu, X. and Boyle, L. N. (in preparation). Effectiveness of intersection movement assist (ima) warnings based on partial least squares (pls) path modeling. *Transportation Research Part F: Traffic Psychology and Behaviour.*

Wu, X. and Boyle, L. N. (submitted). Auditory warning messages within an intersection movement assist (ima) system: Effects of speech and non-speech based cues. *Human Factors: The Journal of the Human Factors and Ergonomics Society.*

Wu, X., Boyle, L. N., and Marshall, D. (2015). Sampling biases associated with driver distraction tasks in a simulated environment. In *Proceedings of the Human Factors and*

*Ergonomics Society Annual Meeting*, volume 59, pages 1621–1625. SAGE Publications Sage CA: Los Angeles, CA.

Wu, X., Boyle, L. N., and Marshall, D. (2017). Drivers avoidance strategies when using a forward collision warning (fcw) system. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 61, pages 1939–1943. SAGE Publications Sage CA: Los Angeles, CA.

Wu, X., Boyle, L. N., Marshall, D., and OBrien, W. (2018). The effectiveness of auditory forward collision warning alerts. *Transportation Research Part F: Traffic Psychology and Behaviour*, 59:164–178.

Xiang, W., Yan, X., Weng, J., and Li, X. (2016). Effect of auditory in-vehicle warning information on drivers brake response time to red-light running vehicles during collision avoidance. *Transportation research part F: traffic psychology and behaviour*, 40:56–67.

Yan, X., Xue, Q., Ma, L., and Xu, Y. (2014). Driving-simulator-based test on the effectiveness of auditory red-light running vehicle warning system based on time-to-collision sensor. *Sensors*, 14(12):3631 – 3651.

Yang, J., Wang, J., and Liu, B. (2011). An intersection collision warning system using wi-fi smartphones in vanet. In *GLOBECOM*, pages 1–5.

Zhang, Y., Yan, X., Li, X., and Xue, Q. (2016). Drivers eye movements as a function of collision avoidance warning conditions in red light running scenarios. *Accident Analysis & Prevention*, 96:185–197.

Zhang, Y., Yan, X., and Yang, Z. (2015). Discrimination of effects between directional and nondirectional information of auditory warning on driving behavior. *Discrete Dynamics in Nature and Society*, 2015.