Integrating Automobile Multiple Intelligent Warning Systems: Performance and Policy Implications

by

ANGELA WEI LING HO

B.S. Computer Science
Carnegie Mellon University, 2004

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements of the Degree of

MASTER of SCIENCE in TECHNOLOGY AND POLICY

at the
Massachusetts Institute of Technology
September 2006

Signature of Author ....
Technology and Policy Program, Engineering Systems Division
August 17, 2006

Certified by..
Mary L. Cummings
Assistant Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by..
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

Integrating Automobile Multiple Intelligent Warning Systems: Performance and Policy Implications

by

Angela Wei Ling HO

Submitted to the Engineering Systems Division

On August 17, 2006 in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Technology and Policy

Abstract

Intelligent driver warning systems can be found in many high-end vehicles on the road today, which will likely rapidly increase as they become standard equipment. However, introducing multiple warning systems into vehicles could potentially add to the complexity of the driving task, and there are many critical human factors issues that should be considered, such as how the interaction between alarm alerting schemes, system reliabilities, and distractions combine to affect driving performance and situation awareness. In addition, there are also questions with respect to whether there should be any minimum safety standards set to ensure both functional and usage safety of these systems, and what these standards should be.

An experiment was conducted to study how a single master alert versus multiple individual alerts of different reliabilities affected drivers' responses to different imminent collision situations while distracted. A master alert may have advantages since it reduces the total number of alerts, which could be advantageous especially with the proliferation of intelligent warning systems. However, a master alert may also confuse drivers, since it does not warn of a specific hazard, unlike a specific alert for each warning systems. Auditory alerts were used to warn of imminent frontal and rear collisions, as well as unintentional left and right lane departures. Low and high warning reliabilities were also tested. The different warning systems and reliability factors produced significantly different reaction times and response accuracies. The warning systems with low reliability caused accuracy rates to fall more than 40% across the four warning systems. In addition, low reliability systems also induced negative emotions in participants. Thus, reliability is one of the most crucial determinants of driving performance and the safety outcome, and it is imperative that warning systems are reliable. For the master versus distinct alarms factor, drivers responded statistically no different to the various collision warnings for both reaction times and accuracy of responses. However, in a subjective post-experiment assessment, participants preferred distinct alarms for different driver warning systems, even though their objective performance showed no difference to the different alerting schemes.

This study showed that it was essential to design robust and reliable intelligent warning systems. However, there are no existing safety standards today to ensure that these systems are safe before they are introduced into vehicles, even though such systems are already available in high-end cars. Even though there are tradeoffs in having standards, such as increased time-to-market and possible loss of innovation, I recommend that safety standards be set nonetheless, since standards will ensure the safety performance of warning systems, to an extent. In terms of functional safety, safety standards should be performance-based, and should specify a minimum level of reliability. In terms of usage safety, the standards should also be performance-based, where driving performance can be indicated by measures such as reaction time, lane position, heading distance and accuracy of responses. In addition, multiple threat scenarios should also be tested. In terms of design guidelines, the various human factors guidelines from different countries should be harmonized internationally to ensure that manufacturers have access to a consistent set of guidelines. Finally, it is also important that these standards, especially for usage safety, specify tests with not just the average driver, but also with peripheral driving populations including novice and elderly drivers.

Thesis Supervisor: Mary (Missy) Cummings
Title: Assistant Professor of Aeronautics and Astronautics

Acknowledgments

First of all, I'd like to thank my advisor, Missy for all her advice and guidance throughout my masters program at MIT. Thank you for believing in me, for giving me countless opportunities, for supporting me, and for pushing me constantly so that I could only become better. I truly appreciate everything that you've done for me and for all the challenges that were presented to me. I've definitely become a better and stronger person throughout this process. Thank you so much for being my mentor here at MIT.

I'd also like to thank the following people for their invaluable help and pointers in polishing my thesis: Jake Crandall, for his time, patience and suggestions on improving the thesis, Dr. Steven Strang for his support and comments on helping me learn and improve my technical writing skills, and Stacey Scott, for all her support, insights and help.

This project would not have been possible without The Ford Motor Company, and I'd like to especially thank Louis Tijerina and Dev Kochhar for their support, insightful comments, and help throughout this project. I have truly enjoyed this project and have learned so much from both of you.

In addition, I'd like to thank The Age Lab, especially Dr. Bryan Reimer for all his patience and help in answering my questions, as well as providing invaluable tips on dealing with "Miss Daisy", Dr. Joseph Coughlin for listening, and the rest of the students and staff of The Age Lab who made my transition smooth and welcomed.

I'd also like to thank the following people for their help in providing insights and comments that enabled me to have a better grasp of the big picture and critical issues: Dr James Foley, Dean Chang, Dr. Thomas Granda, and representatives from General Motors, Hyundai, and Toyota, who responded kindly to my questions and provided me with invaluable information. Professor John Lee was also very helpful and insightful with comments and suggestions on improving the thesis.

I'd like to thank all the students and staff of HALAB (go HALiens!), who have made my time here very memorable. I'd like to thank especially Enlie, Paul, Chris, Mark, Jinho, Jessica, Amy, Cristin and Sylvain for all their help and support in one way or the other. I'd also like to thank Andrea for her help in assisting with the project.

The following people have also been very supportive: Sydney, Dava, Frank, Dean Staton and Marie Stuppard. Thank you for your concern and advice.

Last but not least, I'd like to thank the following people who have been with me throughout the process, and who have provided support in one way or the other right from the start: Grace, for just being there and listening to me, providing me with very insightful analysis and support. I'd also like to thank SGI-USA members, especially "Wave of the Future" district members and leaders including Anne, Teena, So, Rynda, Kathryn, Rinat who provided me with countless encouragement and support. This thesis and what I've experienced is actual proof, and I feel extremely fortunate to have the strategy of the L.S. with me wherever I go. I'd like to thank two especially dear friends, Jiamin and Mi-Hyun, my two MyoHo Sisters who have been with me, encouraging me, and chanting fighting daimoku right from the start to attain BH in this lifetime, to combat our FD, to do our HR, and to show actual proof with the oneness of self and the environment. Finally, I'd like to thank the bunch of Singaporean friends here, who create an excellent network of support and fun!

Last but definitely not the least, my parents and my sister Grace for everything.

Contents

List of Figures

List of Tables

Nomenclature

Acronyms

ABS	Antilock Braking Systems
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management Systems
AVSS	Advanced Vehicle Safety Systems
BLIS	Blind-Spot Information System
CAS	Collision Avoidance Systems
CVO	Commercial Vehicle Operations
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
FCW(S)	Forward/Frontal Collision Warning (System)
FMVSS	Federal Motor Vehicle Safety Standard
FOT	Field Operational Test
FP	False Positives
FVFA(WS)	Follow Vehicle Fast-Approach (Warning System)
GPS	Global System
GPWS	Ground Proximity Warning System
HUD	Heads-Up Displays
ISO	International Standards Organization
ITS	Intelligent Transportation Systems
IVBSS	Integrated Vehicle Based Safety Systems
IVI	Intelligent Vehicles Initiative
LOA	Level of Automation

LDW(S)	Lane Departure Warning (System)
MRT	Multiple Resource Theory
NHTSA	National Highway Traffic Safety Administration
OOP	Out of Position
PRP	Psychological Refractory Period
SA	Situation Awareness
SAE	Society of Automotive Engineers
SDT	Signal Detection Theory
TCAS II	Traffic Collision Avoidance Systems II
TP	True Positives

Chapter 1

Introduction

According to the National Highway Traffic Safety Administration (NHTSA), there are more than 40,000 deaths on highways in the United States each year in spite of the increasing public concern and awareness of the use of safety restraints and safe driving practices. Thus, other approaches are needed to improve safety and alleviate the number of highway accident. One of the most promising is through the use of intelligent driver warning systems, which respond to changes and threats in the immediate operating environment by alerting operators to potential hazards. Intelligent warning systems have been shown to have safety benefits in other transportation domains like aviation, and they are already being used in a variety of systems including aircrafts, nuclear power and chemical plants and medical instruments. While they are not fully deployed in the automobile industry yet, intelligent warning systems could potentially increase safety on the roads by mitigating the effects of time- and safety- critical events.

In the public domain, the U.S. Department of Transportation is focusing research on a variety of Collision Avoidance Systems (CAS) as part of the Intelligent Vehicles Initiative (IVI) set up in 1998. IVI's mission is to reduce the number and severity of crashes by using various intelligent driver warning systems. In particular, the initiative focuses on implementation strategies and technologies of intelligent warning systems in both vehicles and the roadway infrastructure. It also calls for the study of driving performances of different populations of drivers when using such avoidance and warning systems [1]. Lessons learned from the IVI led to the development of another Federal ITS Initiative in 2004: the Integrated Vehicle Based Safety Systems (IVBSS) initiative. Unlike the IVI which was only focused on individual intelligent warning systems, the IVBSS initiative focuses on issues dealing with the integration of multiple intelligent driver warning systems, as well as issues regarding the partnership between the various industries in order to accelerate the introduction of integrated vehicle-based safety systems into the United States vehicle fleet [2].

In the private sector, automotive manufacturers also recognize the value that such warning systems would add to drivers. Even though improvements in passive safety features like seat belts, crash zones, and air bags have reduced the rate of crashes and fatalities, these features are yielding diminishing returns as the fatality rate stagnates [3, 4]. Thus, automotive manufacturers are turning their attention from passive to active safety systems including intelligent warning systems, and they are augmenting current passive safety programs with in-vehicle collision warning and avoidance systems [5]. This shift in trends in the private sector reflects a shift in NHTSA's emphasis from crashworthiness and crash mitigation techniques (e.g., alleviation of the severity of crash-related injuries) to crash avoidance [6].

1.1 Thesis Motivation

This thesis addresses the gap in the research field of multiple intelligent warning systems in the driving domain. Specifically, it will look at two issues. First, it will look at the human factors implications of using alarms with multiple meanings from multiple warning systems, concentrating specifically on problems of confusion over the meaning of alarms leading to a degradation of driving performance. This is important since such emerging technologies in automobiles are still very new, and there are still gaps in the understanding of how drivers will interact with these systems. Second, focusing solely on the technical solutions to these human factors issues is not a holistic way of addressing the problems that may arise with the integration of multiple intelligent warning systems into automobiles. This is especially true since the use of such systems in automobiles will be large-scale and solutions should extend beyond the engineering solutions to encompass regulatory solutions as well. Thus, this thesis will examine possible regulatory policies that could be implemented to mitigate the human factors problems that arise with the integration of multiple intelligent warning systems into cars.

Driving in a dynamic environment can be a complex task, as it requires drivers to visually track objects, monitor constantly changing driving situations and road conditions and make decisions under potentially high workload. The complexity of the primary driving task has been further increased by the proliferation of in-car technologies and telematics, including systems that aid the driver in control and navigation, as well as entertainment and communication devices. Introducing multiple warning systems into vehicles could potentially add to the complexity of the driving task, and there are many critical human factors issues that should be considered.

In the driving human factors research, most of the focus thus far has focused on driver performance using a single warning system and has emphasized the design and development of warning systems in isolation. In addition, research has also been conducted on issues like false and ambiguous alarms, trust in the warning systems, and alarm alerting strategies and modalities [7-11]. While these studies have comprehensively examined a number of critical issues in the introduction of intelligent predictive alarms into the driving domain, there is a dearth of research focusing on driving performance in the presence of multiple warning systems in general: in particular, on a driver's ability to discern the meaning of the warnings in the presence of multiple intelligent warning systems.

For example, one human factors concern is the confusion over the meaning of the alarms caused by the presence of multiple alerting systems. Confusion over the meaning of alarms is two-fold. First, a separate alarm for each kind of hazard may result in too many alarms, making it difficult for drivers to recognize and remember the meaning of each alarm. Second, when the same alarm sound is used to represent multiple meanings, mode confusion may result when drivers do not know which hazard condition the alarm is warning against. If the driver responds erroneously to the warning alarm because of confusion over its intended meaning, not only would the warning system be rendered useless, but it may also lead to worse driving performance. As warning systems become increasingly ubiquitous in cars of the future, this problem will no doubt be a growing concern.

In addition to these human factors issues, there exist important questions about whether there should be any minimum safety standards for intelligent warning systems and, if so, what these standards should be. In addition, there are also questions with regard to whether intelligent warning systems should be standardized across the different automobile manufacturers and suppliers. Problems of confusion over the meaning of the alerts may be exacerbated, especially if the warning systems are not standardized and if the implementation philosophies of the warnings are inconsistent [12]. Thus, another design choice is to allow drivers to customize or personalize these warning systems, and there may be advantages in doing so. This may be especially relevant if the problems of confusion will be mitigated if drivers recognize what the alarms mean, since they were the ones who customized them. Thus, possible regulatory decisions include enforcing minimum standards across manufacturers, as well as giving manufacturers the option of designing customizable warning systems for their users.

1.2 Research Questions

As previously discussed, there are growing desires to achieve higher safety levels in the complex operating environment of driving by providing multiple active intelligent warning systems. However, as these warning systems become increasingly pervasive and as the driving task becomes increasingly complex, unintended consequences may arise, which could lead to situations that are worse than if the systems were not used at all [13].

The goal of my thesis is thus to answer the following questions:

1. What are the human factors implications of using alarms with multiple meanings from multiple intelligent warning systems in the automobile? In particular, are there problems of confusion over the meaning of alarms, and, if so, what conditions will exacerbate this problem?
2. Should there be minimum safety standards for intelligent warning systems in automobiles to mitigate possible human factors problems and to increase overall safety? If so, what should these safety standards be and what are the implications of the policy decision to enforce the safety standards?

1.3 Thesis Scope

This thesis will focus on intelligent warning systems in automobiles, particularly light private vehicles driven by the public; commercial vehicles such as trucks and buses will be out of the scope. In addition, the thesis will concentrate on safety-critical warning alarms that are auditory, as opposed to visual or haptic. Even though the context in question is multiple intelligent warning systems, this thesis will focus on alarms that occur discretely, i.e., multiple threat scenarios leading to alarms that are presented simultaneously will not be considered. Lastly, this thesis will focus on *passive* intelligent warning systems that leave the ultimate reaction decision to the operator. Warning systems that *actively* mitigate the hazard without waiting for a response from the operator will be out of the scope of this thesis.

Although issues arising from the use of multiple warning systems occur in other high-technology domains such as the medical field, nuclear power and chemical plants and in other transportation modes such as aviation, maritime or railway, this thesis will focus only on the domain of automotive transportation.

Throughout the thesis, the terms “alarms,” “alerts,” and “warnings,” will be used interchangeably to mean the same thing: alarms from the warning systems alerting the operator to a potential hazard.

1.4 Thesis Overview

This thesis is structured as follows: *Chapter 2* will provide a literature review of related work as well as provide a framework for understanding the solutions seeking to answer the research questions. *Chapter 3* will address the first research question on human factors implications. *Chapter 4* will address the second research question on the broader institutional issues. *Chapter 5* will conclude this thesis.

Chapter 2

Background and Related Work

This chapter provides an overview of different types of intelligent driver assistance and warning systems including those in the United States market today. In addition, an overview of human factors concerns is provided including a review of selected literature relating to intelligent driver warning systems. The last section provides background on the institutional issues that arise with respect to the question of setting minimum safety standards for these intelligent driver warning and assistance systems.

2.1 Advanced Driver Assistance Systems (ADAS)

Driving is composed of three major categories of activity from a task/function analysis perspective: vehicle control, navigation and collision avoidance, all of which contribute to the overall workload of the driver [14]. With practice, most drivers can perform these tasks relatively well under normal driving conditions. Nevertheless, driving is a dynamic control process and as the demands of the driving task increase due to increasing environmental complexity, the number of critical hazards that drivers encounter will increase as well. Thus, there is motivation to support drivers with Advanced Driver Assistance Systems (ADAS), which are systems that assist drivers in the driving task. Examples of support provided by ADAS include automated assistance in maintaining control, as well as prevention of accidents and navigational assistance. ADAS that prevent collisions are also known as intelligent driver warning systems. ADAS alert drivers to critical states via warnings, and with as number of ADAS in vehicles increases in the future, the number of warnings in vehicles will likely also increase.

Intelligent driver warning systems (or intelligent warning systems in this thesis) have to be robust and reliable stand-alone systems in order to assist drivers and they should not add to the complexity of the driving task. In addition, the design and development of these warning systems cannot be done in isolation from each other; it is imperative that they are compatible with each other and integrated because vehicles in the future will have multiple intelligent warning systems that warn of different hazards [15]. For example, in the event of a multiple threat scenario, if the alerts from multiple warning systems are not well coordinated, they may compete for the driver's attention. The driver may become confused as a result of the different warnings and may be unable to cope with them. Degraded driving performance may even result from the presence of multiple intelligent warning systems that are not integrated As a result, there are risks associated with the introduction of ADAS into the market including safety risks for the driving consumers, and financial and legal (e.g., product liability) risks for the manufacturers arising from these unintended safety consequences.

Nevertheless, in spite of these risks, there is support for the development of ADAS from both the private and the public sectors because of the potential benefits that ADAS bring, including increased safety. In the public sector, ADAS have achieved recognition on a federal level; the United States government has set up various initiatives to study them and facilitate their deployment, which will be discussed in Section 2.1.1. In the private industry, automotive manufacturers have also supported the development of these systems, and this support can be seen in the increasing trend of more manufacturers offering such warning and assistance systems with their vehicles. The intelligent driver warning systems that are already available in the market today will be illustrated in Section 2.1.5. In addition, the private industry has also come together in various consortiums such as "Integrated Project PReVENT" to develop these systems more effectively [16].

2.1.1 Federal ITS Initiatives

The United States Department of Transportation (DOT) has set up a series of initiatives that study Intelligent Transportation Systems (ITS) and their deployment in the US. ITS initiatives can generally be classified according to their functions, including the following: Advanced Traveler Information Systems (ATIS), Advanced Traffic Management Systems (ATMS), Advanced Vehicle Safety Systems (AVSS), Commercial Vehicle Operation (CVO), and Emergency Management (EM). Of these functions, the one concerned with vehicle-based driver assistance systems and avoidance and warning systems is the AVSS[17].

Two of the many initiatives concerned with AVSS are the Intelligent Vehicles Initiative (IVI) and the Integrated Vehicle-Based Safety Systems (IVBSS) initiative. The IVI was introduced in 1997 and authorized in the 1998 Transportation Equity Act for the 21st Century (TEA-21), as part of the U.S. DOT ITS program [18]. The mission of IVI was to reduce the number and severity of crashes on the roads by using ADAS that assume varying levels of control of the vehicle to help drivers avoid collisions. This mission represented a revolutionary shift in DOT's vehicle-based safety research programs as the programs had previously been focused primarily on crash mitigation techniques and crashworthiness, rather than crash prevention and avoidance. One field operation test (FOT) to evaluate the performance of Rear-End Collision Avoidance systems integrated with an Adaptive Cruise Control (ACC) found that the systems had the potential to prevent 10% of all rear-end crashes [18, 19].

Lessons learned from the IVI initiative, which ended in 2005, led to the development of other federal initiatives including the IVBSS initiative [1]. Unlike the IVI which only focused on warning systems in isolation, the IVBSS initiative is focused on issues dealing with the *integration* of multiple intelligent warning systems. Its overarching goal is to combine existing safety and Collision Avoidance Systems (CAS) into an integrated system that can warn drivers of potential crashes. Existing CAS that are being developed into a single integrated system of intelligent warning systems are the Rear-end Collision Avoidance, Road Departure Collision Avoidance and Lane Change/Merge Collision Avoidance Systems [20].

Rear-end Collision Avoidance Systems, also known as Forward Collision Warning Systems (FCWS), provide drivers with warnings and limited control of vehicle speed to minimize the risk of collisions with lead vehicles (stationary and moving) and objects in front of the equipped vehicle. Rear-end collisions account for 25% of all crashes and are the most likely accidents to be fatal [21]. Road Departure Collision Avoidance Systems provide driver warnings when the vehicle is departing from the intended lane of travel and may provide control advice on the steering or braking response to correct the problem. Road departure collisions account for nearly 20% of all crashes. These collisions, which occur mostly at night on high-speed roads and often involve alcohol, are likely to be fatal as well [21]. Lane Change/Merge Collision Avoidance Systems monitor the relative speed and position of any vehicle beside and behind the equipped vehicle, and provide driver warnings and assistance to drivers during a lane change maneuver. Lane change/merge crashes account for 10% of all crashes [21]. These three systems, the Rear-End Collision, Road Departure and Lane Change/Merge Warning

Systems were chosen to be the focus of the IVBSS initiative because rear-end, run-off-road and lane change/merge crashes together account for the majority of fatal crashes on the roads [2].

2.1.2 Situation Awareness enhanced by ADAS

ADAS are designed to help improve driving safety by enhancing driver's situation awareness in dangerous conditions. Situation awareness (SA) is formally defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future [22]". Thus, there are three levels of SA, each implying different cognitive processes:

- *Level 1 SA – perception*: Perception of basic information.
- *Level 2 SA – comprehension*: Understanding the meaning of that information.
- *Level 3 SA – future projection*: Anticipating and formulating projections about what will happen ahead in space and time.

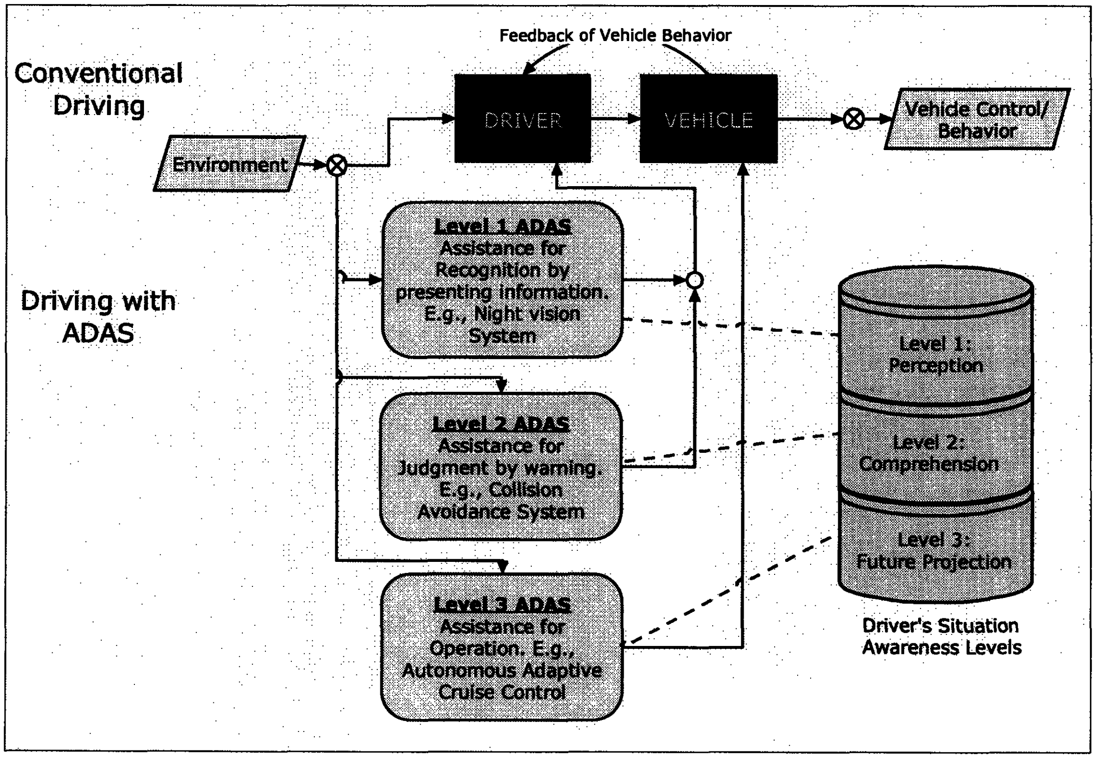


Figure 1: Driver interaction with the vehicle control loop: conventional driving vs. driving with ADAS (adapted from [23])

During conventional driving where no assistance systems are present, drivers have to first perceive and recognize the driving environment, then make a judgment about an impending hazard and the future consequences of any actions they take, and finally, take control of the vehicle and execute the corresponding maneuver to mitigate the hazard. Drivers do these based on monitoring the feedback of the vehicle behavior (Figure 1) [23]. ADAS can thus be broadly categorized into systems that provide these varying levels of assistance to drivers and enhance their situation awareness (Table 1). By enhancing drivers' SA, driver assistance systems will ideally allow drivers to function in a more timely and effective manner. However, it must be noted that ADAS may also cause drivers to have a loss of situation awareness, especially when an actively intervening system actually takes over the operation and control of the vehicle during an impending hazard [24]. Thus, the drivers could be out-of-the-loop if they only monitor the vehicle instead of actually being in control. If drivers do not notice the hazard, they may not understand the warning system's response to the hazard and may become more confused as a result. In general, humans are poor at monitoring tasks when they are out of the control loop [25].

Table 1: Types of ADAS that helps in enhancing different levels of driver's situation awareness.

Enhancing driver's SA level:	Assisting drivers in:	Examples of ADAS
Level 1: Perception	Perceiving and recognizing hazards in the driving environment by presenting information that helps to enhance drivers' perception.	Night vision systems that present information the human eye finds hard to discern in dark backgrounds.
Level 2: Comprehension	Passive mitigation of hazards: Providing judgment of hazards by warning the drivers ahead of time, thus aiding in the driver's comprehension of the hazards.	Collision avoidance systems like Lane Departure Warning System (LDWS).
Level 3: Future projection	Active Mitigation of hazards: Intervening to operate and control the vehicle to avoid the hazard, thus aiding in the driver's anticipation of the hazard.	Autonomous ADAS such as ACC that regulates the vehicle's own speed without input from the driver.

2.1.3 Types of Advanced Driver Assistance Systems (ADAS)

There are many different ways of categorizing ADAS, such as by the level of assistance that they provide to drivers. Three broad categories of ADAS may be distinguished as follows (Figure 2) [24, 26, 27]:

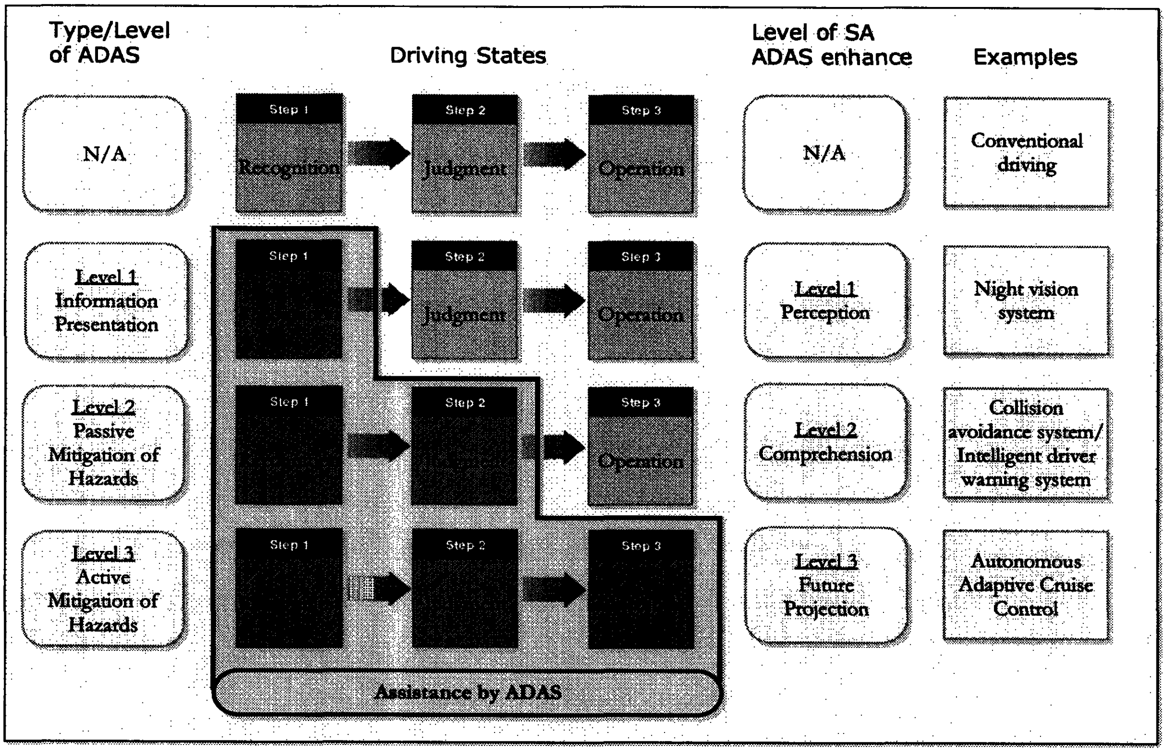


Figure 2: Behavioral Model of a Driver and Level of Driver Assistance (adapted from [23])

The ADAS that provide the least assistance are those that provide Level 1 control. Such systems present information obtained from sensors to drivers and assist drivers only with the recognition of the hazard. Such a system is not a warning system, as it does not provide any warning alerts; instead, it is a system that enhances the perception of drivers. An example is a night vision system that aids the driver in the dark by creating a visual image of the roadway ahead based on thermal imaging technology and infrared sensors, and by providing that image via a Heads-Up Display (HUD). Thus, this system enhances Level 1 SA of drivers, by aiding in their perception of the driving environment.

Level 2 ADAS provide additional aid to drivers by providing assistance for both recognition of the driving environment and judgment of the criticality of hazards by providing warning alarms.

Such ADAS are *passive* intelligent warning systems, as they only warn drivers but do not actively mitigate hazards, unlike Level 3 ADAS. Such systems include intelligent warning systems including Collision Avoidance Systems (CAS), which will be discussed next in Section 2.1.4. Examples of CAS include Forward Collision Warning Systems or Rear-End Collision Avoidance and Intersection Collision Avoidance Systems. Thus, these ADAS enhance Level 2 SA of drivers and aid in the comprehension of the driving environment by alerting drivers to hazards through the use of alarms.

Level 3 ADAS, called *active* intelligent warning systems, are intervening assistance systems that have a higher level of automation and lower level of driver control. These systems provide more assistance to the drivers and mitigate hazards *actively* without input from the driver. The level of assistance or the level of automation (LOA) that the ADAS provide can range from intervening and taking partial control, to full control, which would constitute autonomous driving [28]. These intervening systems relegate drivers from being manual controllers to supervisory controllers. An example is an Adaptive Cruise Control (ACC) System that detects obstacles in front of the driver and intervenes by using evasive measures such as applying the brake to regulate the speed on it own, such that the following distance does not exceed a certain threshold. Thus, such systems enhance Level 3 SA of drivers by helping drivers anticipate and taking action to mitigate the hazard by not only providing warnings, but also by taking partial control of the vehicle. However, as previously discussed, even though these systems may enhance Level 3 SA of drivers, the SA of drivers may also be degraded since drivers are out of the control loop and may not know why the action came about.

2.1.4 Types of Collision Avoidance Systems/ Intelligent Warning Systems

Of all the types of ADAS, the ones with the greatest potential for reducing accidents are the systems designed to predict, avoid and thus, prevent collisions. This is because if these systems are reliable and robust, they can warn drivers of impending collisions through alarms before they occur and can possibly help to prevent collisions. These types of ADAS systems are known as Collision Avoidance Systems (CAS) (otherwise known as intelligent driver warning systems). The main purpose of CAS is to alert drivers to a hazardous situation which requires action, typically to avoid a collision. Additionally, the warnings may also serve to educate drivers by providing feedback concerning desirable driving practices [29]. CAS should generate at least two levels of warnings differing in urgency: imminent and cautionary warnings [15]. Collision Avoidance Systems under development today are generally Level 2 ADAS (see Section 2.1.3) since they assist drivers in both the recognition of the driving environment and the judgment of the hazard by providing warnings to the driver through alarms. They do not actively intervene to mitigate the hazard by controlling the vehicle.

There are two main types of CAS: vehicle-to-vehicle CAS and vehicle-to-infrastructure CAS. Current vehicle-to-vehicle systems use radar and machine vision to trigger a warning when a vehicle is potentially about to collide with another vehicle. Examples of current systems being brought to the marketplace include rear-end collision warning systems or FCWS, and Blind-Spot Information Systems (BLIS). Vehicle-to-infrastructure driver warning systems are systems that warn of a potential collision with the roadway infrastructure. An example of a vehicle-to-infrastructure driver warning system being developed is an intersection collision avoidance warning system. In addition, research and development is underway for introducing more complex systems into the market that use both in-vehicle and infrastructure-based technologies, especially communication and positioning technologies. Thus, in the future implementation of Collision Avoidance Systems, vehicles will detect or communicate with other vehicles as well as with the roadway infrastructure via sensors and telecommunication networks such as Dedicated Short Range Communications (DSRC) and Wide Area Wireless Mobile Communications [30].

While ACC systems available in the market today are not collision avoidance systems since they maintain a preset speed and adjust that speed to maintain a preset following distance from a lead vehicle, they do have warnings that alert drivers when intervention is required. This distinction should be made because ACC systems today are separate systems from Forward Collision Warning Systems (FCWS), which primarily warn of imminent frontal crashes. However, in the future, ACC and FCWS may be merged into the same integrated system that not only controls and regulates speed and following distance, but which also warns of impending frontal collisions. The resulting system will be a Level 3 ADAS, which actively mitigates hazards by providing warnings and by intervening to operate and control the vehicle.

2.1.5 ADAS in the Market Today

ADAS first began to appear commercially in the high-end luxury car models. Mercedes-Benz launched Europe's first ADAS, Adaptive Cruise Control Systems, in 1999. Two years before, Toyota launched the world's first ADAS, Blind Corner Monitor and Radar Cruise Control in Japan [31, 32]. Subsequently, Mercedes-Benz, BMW, and Jaguar introduced ACC in the United States in 2000. In general, the U.S. market trails Europe, and the European market trails Japan by 2 to 3 years [33]. Since then, more manufacturers, including Audi, BMW, Nissan, Jaguar, Lexus, Citroën and Volkswagen have introduced basic ADAS into their fleet of vehicles in the Japan, Europe and the U.S. markets. Nevertheless, these ADAS are still only available as options in selected high-end models and not widely available to the public yet in the United States.

As of the 2005/2006-model year, ADAS available in the U.S. light vehicle market include adaptive headlights, parking aids, navigation aids, night vision systems, and auto-dimming rear-view mirrors [34]. ADAS that enhance drivers' Level 2 situation awareness include those that support longitudinal control of the car, namely Adaptive Cruise Control (ACC), and those that support lateral control of the car, namely Lane Departure Warning Systems (LDWS). Other driver warning systems previously mentioned such as systems that warn of forward collisions, lane change/merge collisions, intersection collisions and blind-spot indications are not available in the U.S. commercial market yet.

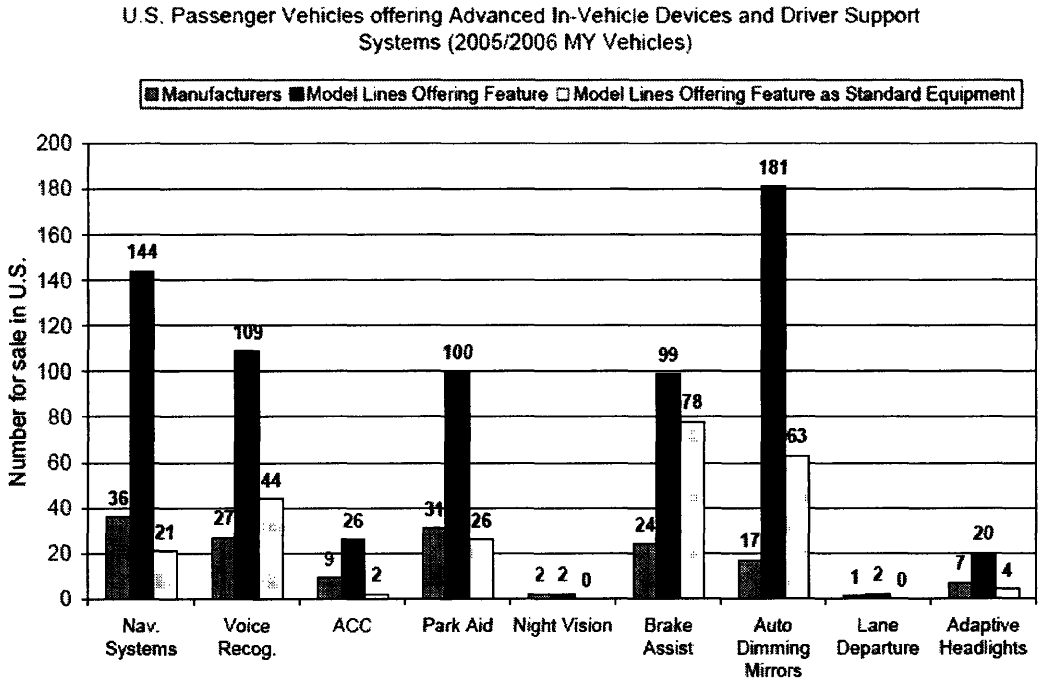


Figure 3: Vehicles equipped with Advanced In-Vehicle Devices in the U.S. (2005/2006 models) [26].

Figure 3 shows the different ADAS offered in the U.S. market today according to the different manufacturers (e.g., Mercedes-Benz, Toyota) and model lines (e.g., E-Class, Sienna). The figure also shows a breakdown of number model lines that offer the ADAS as an optional upgrade, or as standard feature. For example, there are 9 manufacturers in the United States offering ACC, and from these, there are 26 model lines offering ACC as an optional feature. Only 2 model lines offer them as standard equipment. For more details on the breakdown on the ACC system and LDWS for the 2005/2006 models in the United States market, refer to Appendix A.

It can be seen from Figure 3 that the most common ADAS available today are auto-dimming mirrors (available on 244 model lines) and navigational systems (available on 165 model lines). In contrast, ACC (available on 28 model lines) and LDWS (available on 2 model lines) are only limited to high-end manufacturers and are not widely available to the public yet. Nevertheless, these two systems and other driver warning systems previously mentioned are expected to be introduced into vehicles in the future. The following two sub-sections, Section 2.1.5.1 and Section 2.1.5.2 will provide details on the characteristics and design parameters of the ACC system and the LDWS currently available on these model lines. The last sub-section, Section 2.1.5.3, will provide details on how these systems and other ADAS in development vary across different manufacturers.

2.1.5.1 Longitudinal Control Aiding Systems

There are currently nine manufacturers (vehicle makes) offering ACC systems in the U.S.: Audi, BMW, Cadillac, Infiniti, Jaguar, Lexus, Maybach, Mercedes-Benz and Toyota. In general, this technology is only available for high-end luxury sedans, although some entry-level models within luxury brands (e.g. BMW 3-Series) are beginning to offer this feature too [34]. Refer to Appendix A for more details on the model lines in which these ACC systems are available.

Manufacturers market ACC under a variety of names, including Active Cruise Control, Intelligent Cruise Control, Dynamic Cruise Control, and Distronic. Despite their different naming conventions, the systems are functionally similar. For instance, they can only function above the lower threshold of 20-28 miles per hour (mph), and automatically disengage when the speed drops below this minimum operating value (with a warning alert to the driver). Drivers can control both speed and following distance settings and can disengage the ACC using various methods including a brake tap. All systems provide an approach warning (using both audible and visual cues) to indicate when driver intervention is required [34].

Despite some key system function and interface characteristics (e.g., minimum operating speed of 20-28 mph, minimum headway of 1 sec) seemingly standardized across manufacturers, most design aspects of the ACC are still not uniform across manufacturers. For instance, ACC systems differ especially with regard to the location and placement of the controls and displays, the use of warning symbols and how the ACC systems are integrated with conventional cruise control [34].

ACC and warning systems with forward collision warnings are likely to be adopted more widely in the commercial market when empirical data shows that they are effective at preventing collisions [35]. However, empirical data can only be collected when these systems are present in the commercial market. Thus, it is likely that high-end vehicles in the future will be fitted with an integrated warning system that combines current ACC systems with FCWS. If indeed proven to be effective in preventing collisions in the high-end market, then these systems are likely to be more widely adopted and the technology will likely diffuse into a larger market segment.

2.1.5.2 Lateral Control Aiding Systems

At present only Infiniti (the luxury brand of Nissan) offers LDWS in the United States [34, 36]. This feature is optional on two of the luxury model lines: the 2005 Infiniti FX and the 2006 Infiniti M45[37]. Refer to Appendix A for more details on the model lines where these LDWS are available.

The LDWS uses predictive paths to determine when to warn drivers that the vehicle is traveling too close to lane markers. An on-board camera tracks the lane markers ahead up to 25 meters. The system will not operate if the camera cannot detect the lane markers, if the vehicle's speed is below 45 mph, or if the turn signals are activated. If the system determines that there is indeed an unintentional lane departure, warnings that are both visual (indicator light on the instrument panel) and auditory (warning chime) are presented to the driver. The driver can manually disengage the system by using a switch located on the dashboard and an indicator light in the instrument panel provides the system status. There are no options for customizing the sensitivity threshold at which the warning is triggered or the volume of the auditory alert.

Unlike the ACC systems that are available on 28 model lines, the LDWS are only available on two model lines. One of the barriers that limits the number of LDWS in the commercial market is the high costs of cameras and steering actuators which help to provide torque in the steering wheel to help drivers stay in the lane. Nevertheless, if camera costs continue to drop and if the LDWS become more integrated with existing power steering components, then wider adoption of the LDWS may become possible in future vehicles [35].

2.1.5.3 Variability of Intelligent Warning Systems

The intelligent warning systems and ADAS currently available in the U.S. market not only vary across different manufacturers in terms of the interface elements (e.g., graphic displays, controls, warning modalities) and alerting strategy (e.g., level of assistance provided, threshold sensitivity), but they also often vary across model lines within a brand.

In terms of the level of assistance provided, manufacturers differ with respect to active mitigation of hazards. In terms of ACC systems, Mercedes-Benz's Distronic Plus proximity control system on its 2006 models completely halts the car if necessary with a brake assistance program, which adds brake pressure if an impact is expected. Volvo and Honda also have developed ACC systems that actively mitigate hazards, by increasing the brake pressure during an impending collision, although they are not deployed yet. On the other hand, other ACC systems only provide warnings to the drivers and do not actively mitigate the hazard. Such systems include Jaguar's ACC system on its 2003 models.

The warning design also varies across different manufacturers. For example, Mitsubishi's Driver Support System, launched in Japan in 2000, warns the driver with a combination of visual, auditory, and haptic alerts (include steering wheel vibration and steering torque) [38]. Other systems, such as Volvo's Co-Driver, only use auditory warnings to alert drivers of an impending collision [39].

The introduction of these active safety systems offers benefits including increased safety to the public. However, these systems may also introduce new risks and unintended consequences. From a human factors perspective, the wide variations in warning and driver assistance systems may create problems for drivers, especially problems of confusion. These issues will be further explored in the following section, as well as in Chapter 3.

2.2 Human Factors Concerns

The introduction of intelligent alarms into vehicles can potentially increase the complexity of the driving task in a dynamic environment, especially when taking into account the simultaneous proliferation of in-car technologies and telematics (communication technologies that provide information to drivers) including navigational, communication, and entertainment systems. This proliferation of in-car technologies also includes driver warning systems. Multiple uncoordinated and independent systems could result in lower usability than one well-integrated system. For example, an integrated system can coordinate alerts from a multiple threat scenario that overlap in time, and then prioritize and select the right alert to assist the driver. Conversely, in non-integrated systems, different alerts may compete for the driver's attention and may also cause problems of confusion. However, this phenomenon may also arise even in integrated systems. In addition, as seen in the previous section, current intelligent warning systems available in the market today vary widely across manufacturers, and this variability may create problems of confusion for drivers as well.

Thus, as a result of this potential problem of confusion, it is necessary to understand how humans process information and how they respond to a stimulus (e.g., a warning alert). Thus, this section will first discuss human information processing in terms of driver alerting, followed by a literature review of warning systems research, including modalities of alarms, reliabilities of the warning systems, and the possible use of a master alarm alerting scheme for multiple intelligent warning systems in vehicles.

2.2.1 Human Information Processing Model

In order to better understand a driver's reaction to the functions of multiple warning systems, an information processing model developed by Wickens, the multiple resources theory (MRT), is discussed. MRT is one theory of attention and workload that explains how humans simultaneously process multiple tasks [40]. This theory is based on the assumption that people can process some tasks in parallel without sacrificing performance because there are distinct attentional and cognitive resources that differ along several dimensions (Figure 4), which will be further explained:

- *Processing Stages* encompass the three major information processing stages of "perception," "cognition" and "response." Available attentional resources are used for tasks in all the three different stages. For example, in a multiple threat scenario, a driver has to divide his attention between perceiving a hazard ("perception" stage), understanding another hazard ("cognition" stage), and making an appropriate response ("response" stage) to avoid the hazard. MRT explains that a driver requires the same attentional resources to perceive and to understand the hazards (in the "perception" and "cognition" stages), but separate attentional resources to respond to the hazards (in the "response" stage).

- *Processing Codes* refer to the "verbal" and "spatial" processes which can be associated with the two cerebral hemispheres [41]. Thus, attentional resources can be separated to parallel process verbal and spatial tasks. An example of a verbally-coded task is listening to a verbal command, while an example of a spatially-coded task is navigating using visual cues.

- *Perceptual Modalities* include "visual" and "auditory" modalities as the two major channels where information is perceived. Thus, information that is perceived in different modalities uses separate attentional resources. An example of alert information presented through the visual channel is a visual icon flashing on the dashboard. An example of alert information presented aurally is an auditory warning alarm. Although the multiple resources model does not depict the haptic modality, it can also be considered to be a different perceptual modality from the auditory and visual modality.

- *Output Responses* refer to responses which are "manual" and "linguistic/vocal" in nature. An example of a task that requires a manual response is steering the wheel and an example of a task that requires a linguistic/vocal response is verbally acknowledging a hazard or voice dialing the cellular phone. Tasks that differ in their output responses require different attentional resources.

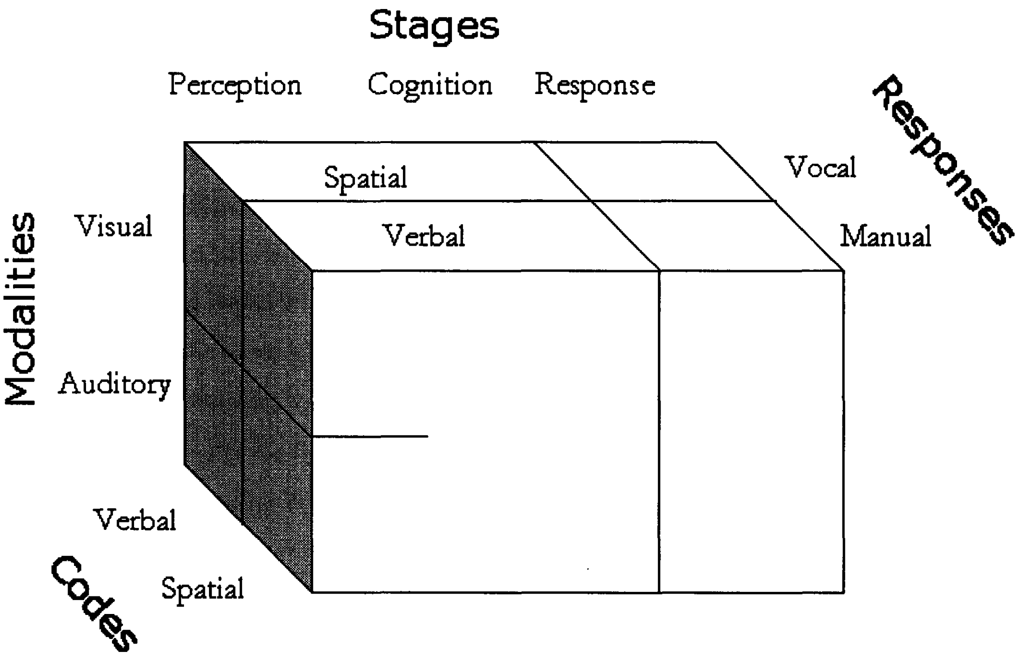


Figure 4: Three-dimensional proposed structure of the processing resources of the multiple resources theory (adapted from [40]).

MRT predicts that tasks will less likely interfere with each other if they occur during different information processing stages (i.e., perception and cognition vs. response), use different modalities of perception (i.e., visual vs. auditory), with different cognitive coding (i.e., spatially-coded tasks vs. verbally-coded tasks), and require different response outputs (i.e., manual output like steering the wheel vs. vocal output like saying a command).

In the same way, two tasks that use similar resources (e.g., two visual tasks that both require a manual response) will more likely interfere with each other and lead to degraded performance. Wierwille suggested that the visual and manual demands of driving are of primary concern, since most of the driving stimulus and information are presented visually and most of the driving tasks require a manual output response [42]. Hence, according to MRT, in a driving environment, using the auditory modality for presenting alarms, as opposed to the visual modality, should improve time-sharing performance [43].

Nevertheless, presenting all alarms aurally could also be problematic. If multiple alarms are presented in close temporal proximity and are presented in the same perceptual modality (e.g., all auditory alerts), then the alarms could interfere with each other. However, if the alarms are presented in different modalities (e.g., auditory, visual and haptic), then because drivers will use separate attentional resources to process information, task-sharing performance could possibly be improved. Consequently, using multi-modal (e.g., auditory, visual and haptic) information could lead to increased efficiency in information processing through redundant coding of the information across various sensory channels. The advantages and disadvantages of using auditory alarms, as well as the other modalities and multi-modal alarms will be further explored in Section 2.2.3.1.

2.2.2 Two Main Human Factors Concerns: Prioritization and Confusion

When multiple intelligent warning systems (both independent or integrated) are present in a vehicle, two fundamental concerns arise which need to be addressed. First, there are issues with regards to prioritization of alarms. Since multiple warning systems are present, there is the possibility of multiple alarms activating simultaneously, or in close sequential succession. Humans have a Psychological Refractory Period (PRP) that limits the ability to respond to stimuli which are presented in close temporal proximity [44]. Hence, the reaction time of drivers may be delayed when warnings are presented in rapid succession with other warnings during a multiple threat scenario. In addition, warning information from these alarms may overburden drivers and compete for drivers' attention, leading to a longer time for drivers to respond to the hazard. As was just discussed, the MRT predicts that this delayed response will occur especially when the modalities of the alarms and target response are the same [45]. Thus, it is important to ensure that multiple alarms from different warning systems do not occur in rapid succession. One solution is to assign relative priorities to hazards based on safety relevance to drivers [46]. Thus, a higher priority warning will take precedence over a lower priority one and suppresses it so that the alarms do not sound at the same time.

Second, there are issues of confusion over the meaning of the alarms caused by multiple alerting systems. A unique alarm for each hazard type might result in too many alarms in the vehicle, thus making it difficult for drivers to recognize and remember the meaning of each alarm. However, if the same alarm sound is used to represent multiple meanings, mode confusion may result when drivers do not know which hazard condition the alarm is warning against. In this case, drivers may take a longer time to respond because they will first have to understand the alarm and determine what hazards it is warning against, before executing a final response.

When the driver misinterprets or misdiagnoses the alarm, he/she may commit an error of commission and respond erroneously to the alarm. This would result in rendering the warning systems useless and lead to degraded driving performance. Thus, it must be ensured that the warning systems assist, rather than confuse the driver. Warning systems should not only alert drivers to the presence of hazards, but should also communicate the type of hazard and facilitate the appropriate response.

This thesis focuses on the second fundamental concern that alarms from multiple warning systems, even if they occur discretely, may confuse drivers.

2.2.3 Review of Intelligent Warning Systems Research

This section gives an overview of the research that has been done in the area of intelligent warning systems. Most of the research thus far has focused on driver performance using a single warning system and has emphasized the design and development of warning systems in isolation. In particular, much of the research has been conducted on the driver warning systems interface in terms of modalities. The effectiveness of warning systems has also been studied, including multi-staged (or graded alarms) versus single-staged alert strategies for potential collisions [8], and the effectiveness of warning systems on different age groups [7, 47, 48]. Other related human factors concerns have also been investigated, including responses to nuisance and false alarms [29, 49], trust in automation (both too much and too little trust) [50], mistrust in the automation leading to disuse of the systems [51, 52], level of autonomy given to the warning systems, distraction caused by the alarms [53], over- [54] and under-reliance on the warning systems [15], perceived criticality and urgency of alerts [55] and driver acceptance [56].

To further investigate the human factors issues that are most relevant to the focus on multiple alarms, the following research areas will be further explored in this section: alarm modalities, warning system reliability (false and missing alarms) and the use of a master alert in multiple warning systems.

2.2.3.1 Alarm Modalities

Several studies have been conducted to determine the effectiveness of intelligent alerting systems, particularly on the effectiveness of alarms transmitted through the visual [11], the audio and the haptic [10] channels in vehicles. Research has shown that the auditory modality generally seems to be best for conveying warning signals as it appears to reduce reaction time as well as not overload the visual channel, which is especially relevant for driving tasks [10, 48]. MRT predicted that this would hold true since there is high demand on the visual channel of drivers as the driving task mainly involves tracking and monitoring. Thus, if the intelligent driver warning systems use visual displays exclusively, drivers may experience attention overload which directly affects the perception-to-response time to stimulus [57]. Auditory alarms tend to have an advantage in being omnipresent, omni-directional, and for having the ability to get the driver's attention quickly regardless of where their initial attention is focused [58]. This is especially important in a time and safety critical scenario where immediate attention and reactions are warranted. In addition, auditory alerts have also been found to be superior to visual stimuli in facilitating the correct responses [15, 59].

Auditory alerts are generally classified into three main types: verbal/speech, tonal signals warnings and auditory icons, each of which have various advantages and disadvantages [60]. Verbal warnings have the advantage of directly conveying the danger to the driver (e.g., "frontal collision, frontal collision") or providing direct solutions to the operator in terms of follow-up steps to avoid the hazard (e.g., "Climb, climb, climb!" of GPWS). Thus, verbal warnings tend to be unambiguous and efficient. However, one main disadvantage of verbal alarms lies in the difficulty of discerning the warning over background conversations. Moreover, complex verbal warnings also require more cognitive and attentional resources and therefore may not be suitable for time- and safety- critical events [46, 61].

Tonal signals, on the other hand, have the advantage of having a commonly recognized meaning as a result of consistent usage. Tonal signals are also favorable when compared to verbal warnings since they will not mask other forms of communications. Tonal alerts also result in quicker reaction time as compared to speech alerts in general [62]. However, tonal alarms have the inherent disadvantage of not representing the situation they are trying to convey. Also, they cannot be ignored easily, which can become a nuisance when there is a high incidence of false alarms from the warning systems [63]. In addition, research has also found that the large number of auditory signals used in military aircraft, including tonal alarms, made it difficult for the crew to recall the meanings of the warnings [64]. Moreover, some non-speech signals are sufficiently similar that they may be confused, particularly in high workload situations. Thus, tonal auditory alarms are most likely to cause confusion over since there is usually no straightforward mapping of the tone to the hazard [65].

Auditory alarms should be able to communicate the nature of the hazards to the operators through an inherent mapping of the sound to the hazard [66]. Besides using verbal alerts that explicitly communicate the hazard or the follow-up response to take, another alert type that can convey the nature of the hazards to drivers are auditory icons. Auditory icons are representational sounds that have stereotype meanings defined by the objects or actions that created the sound [67]. Examples include glass breaking or tires screeching to indicate a collision, or a virtual rumble strip to indicate lane departure. Research has demonstrated that auditory icons appear to produce faster reaction time than conventional auditory warnings (tonal and verbal), but more inappropriate responses [9, 68]. Thus, they have not been successfully implemented because of the incorrect association of the auditory icons to the actual events [68].

To allow auditory alarms to convey more information, research has demonstrated that *spatial* auditory alarms have been shown to significantly improve performance in both the aviation and automotive domains [69, 70]. Three-dimensional auditory displays are being developed to enhance cockpit displays in military aircrafts [71]. Spatially-located warnings are also relevant in vehicles, where they can be used to indicate the direction of the potential hazard (e.g., blind spot/side, forward, rear). An example of an intelligent warning system that uses spatially-located auditory alarms (in particular, auditory *icons*) is a Lane Departure Warning System, where alerts are presented through the left or right speaker in the car, depending on whether the driver is unintentionally departing left or right from his lane. The auditory icon in this case could be a rumble strip sound to represent the sound drivers hear when they leave their lanes.

As compared to visual and auditory displays, haptic displays are not widely used in automobiles. Research has shown that haptic alerts should generally be used in combination with visual and/or auditory warnings. This is because haptic alerts often do not convey the representational meanings of the hazards in order for drivers to form a natural association between the hazards, the warnings, and the appropriate actions to take. As a result, haptic alerts alone are not often effective [29]. For example, pedal pressure may be a good warning to indicate a braking response because of the natural association between the pedal pressure and response; however, it is a less effective warning for communicating an unintended lane departure as there is not such natural associations [72].

In spite of all the advantages of auditory alarms, they cannot be used exclusively in the driving environment due to various limitations of the user population, such as degraded hearing abilities. Research has shown that multi-modal displays may be effective, and performance generally improves when auditory alerts are used in combination with and are redundant to visual and haptic displays [73, 74]. This is in line with MRT since redundant displays make it more likely that an unused resource can be allocated to a new potential hazard. Thus, task-sharing performance will improve when attentional and cognitive resources can be allocated to tasks that differ in the perceptual modality dimension.

One of the research questions of this thesis is to investigate the implications of using aural alarms with multiple meanings in the context of multiple intelligent warning systems. Since research has shown that aural alarms are generally more suited for imminent warnings and are more prevalent in vehicles today than multi-modal alarms, this thesis will focus on the aural channel only, in spite of the potential benefits of multi-modal warning systems.

2.2.3.2 Warning System Reliability - False and Missing Alarms

When multiple intelligent warning systems are present in the vehicle, driver performance may be degraded in many ways. In addition to confusion which was discussed previously, multiple intelligent warning systems can also degrade performance when the warning systems have a high incidence of false and missing alarms (Table 2). A false alarm may lead to a sudden reaction from a driver when no collision is imminent. Thus, when a driver reacts to a nonexistent situation because of a false alarm, the wrong identification or no identification of the hazardous situations may be a source of distraction and confusion to the driver, which subsequently degrade his driving performance. In addition to false alarms, warning systems may also fail to warn of legitimate dangers, which result in missing alarms. Thus, both false and missing alarms can undermine driver's confidence in the warning systems and the subsequent willingness to trust and use the warning systems [51].

Table 2: Signal Detection Theory Table

		Response (i.e., warning alarm)	
		Present	**Absent**
Signal/Stimulus **(i.e., critical hazard)**	**Present/Signal**	Hit - True Positive	Miss(ing) Alarm Type 1 Error – too stringent decision criteria
	Absent/Noise	False Alarm Type 2 Error – Erring on the side of caution	Correct Rejection

Warning systems depend on sensors to detect if the criteria or threshold has been exceeded or violated. When the cost of a missed signal is high, the decision criteria will tend to be conservative. However, while a conservative design helps ensure adequate reactions to critical situations, it also increases the frequency of false and nuisance alarms [51, 75]. For example, the decision criteria of collision avoidance and warning systems in automobiles may tend be conservative, especially to address the variance in sensor measurements and unpredictability in the dynamics of the warning systems [76]. With such a decision criteria, nuisance alarms may also be common. Nuisance alerts occur when the alarms are correctly generated based on a threshold violation, but trigger because of insignificant hazards. Thus, false and nuisance alarms may create a false sense of urgency and divert the attention of drivers. Although the warning systems are performing to pre-defined threshold criteria and specifications, these false and nuisance alarms will appear as failures of the systems to drivers.

In general, critical hazards such as imminent collisions with a lead vehicle or a stationary object have very low base rate in reality. Thus, if the false and nuisance alarm rates are high despite a low a priori probability of critical events, then drivers' confidence in the warning systems will drop [51]. As the number of false alarms increases, drivers will gradually change their attitudes and beliefs about the warning systems. They may lose confidence and not trust the warning systems anymore. Consequently, this change in attitude and beliefs will affect their motivation to accept and use the systems. As more false alarms get presented, drivers may become annoyed and distracted. If drivers choose to ignore the alarms, then the purpose of having warning systems is defeated. However, if drivers take more time to decide their response, then the warning systems are less effective. As a result, the presence of warning systems with a high false alarm rate, especially for real events with a low base rate, may degrade overall driving performance.

Elimination of all false alarms is thus ideal, but according to the Signal Detection Theory, the balance of false alarms and missing alarms is a tradeoff that has to be optimized. Thus, the selection of an appropriate decision criterion with a threshold that balances the incidence of missing with the early detection of alarms is crucial. Elimination of all false signals is ideal, but attempts to achieve that goal by altering sensor detection decision criteria can lead to overly strict detection systems that fail to alert of true hazards. Instead of generating too many false alarms, warning systems may thus fail to inform of legitimate danger, leading to the converse problem of missing alarms [77]. If the sensor's decision criteria is set too strictly, then the sensor may fail to signal developing crises (i.e., missing alarms), or it may wait too long before warning the operator (i.e., late alarms). Missing alarms are detrimental as they often lead to operator mistrust in the warning systems [51].

Warning systems with many false or missing alarms are unreliable systems. Research has shown that excessive problems of false alarms on comparable aircraft intelligent collision avoidance warning systems, such as the TCAS, have had negative impacts due to operators' mistrust and a lack of usage [78]. Similarly, in vehicles, not only will low reliability of the warning systems affect drivers' trust and acceptance of the systems, it can also dramatically and negatively influence driving performance [8, 79-81]. If there is a high incidence of false and missing alarms, drivers may be better served by not having such intelligent aids at all. Thus, well chosen warning criteria and decision threshold are important factors that can ultimately affect the market acceptance of these intelligent warning systems. As a result, there is a crucial need for the development of highly reliable intelligent warning systems. However, this task will not be trivial since the configurations of the driving environment are constantly changing.

2.2.3.3 Multiple Intelligent Warning Systems

When multiple warning systems are present, critical issues unique to the integration of multiple intelligent warning systems include issues of alarm prioritization [82] and conflicting and contradictory alerts from separate warning systems [83]. Presentations and modalities of multiple warning systems have also been investigated, specifically the effects of graphic versus text displays on driver reaction time when warnings from different warning systems were presented simultaneously [84].

Even though there has been some research on multiple warning systems such as those just outlined, there is a dearth of research on driver performance and interaction with multiple intelligent warning systems. In particular, the option of using a master alert as a general alarm as opposed to using distinct alarms for separate warning systems has not been adequately explored. Individual alarms for the different warning systems may have disadvantages because a unique alarm for each hazard type may result in too many alarms in the vehicle, making it difficult for drivers to recognize and remember the meanings of alarms, as they become overloaded and confused. Thus, this thesis is addressing the alternative design choice of using a single master alarm and exploring if a master caution alert for multiple warning systems will make a difference in improving or degrading driver performance.

A single master alarm has the advantage of communicating the presence of a hazard through a consistent alert, and drivers will learn to associate that master alert with danger. However, while the master alert is synonymous with critical situations, it does not necessarily communicate the hazard type effectively. Thus, drivers will need to direct their attention towards locating the specific hazard causing the alarm. In cases where the target responses to the multiple alarms and hazards are very different, it may be insufficient just to alert of the *presence* of a hazard by a master alert. For example, an FCWS may warn of a hazard in front of the driver, which requires a braking response, while a LDWS may warn of unintentional lane departure, which requires a steering correction. Thus, a master alarm alerting of both an imminent forward hazard and an unintentional lane departure may be insufficient. The additional time required for drivers to locate the specific hazard and to make an appropriate response may negate the benefits of a single master alarm warning strategy. In addition, another disadvantage of using a single master alarm is mode confusion that may result because the same alarm is used to represent multiple meanings. As a result, drivers may not know which hazard condition the alarm is warning against.

It is important that alarms are informative in alerting drivers to the condition at hand, without unnecessarily overwhelming them with too much too often or inadequately. Such information may be embedded in the nature of the alarm (i.e., a verbal warning or auditory icon), or may come from the driver awareness of the context [85]. Thus, the issues concerning the presence of a master alerting scheme of multiple intelligent warning systems in vehicles have yet to be adequately addressed.

2.3 Institutional Concerns

In addition to technical issues, there are various institutional considerations that will also add to the complexity of the development and implementation of intelligent driver assistance and warning systems [86]. Institutions may be defined as any form of codes that people develop to determine how components in society interact. These codes include formal codes, such as judicial legislation, economic rules and contracts, and informal constraints, such as social conventions and codes of behavior [87].

Three main institutional issues arise that need to be addressed in conjunction with the technical development of these systems. First, there are uncertainties concerning the safety impact of large-scale application of intelligent driver warning systems. It is possible that the intelligent warning systems may instead lead to worse performance than if they were not present at all [88]. There is no clear empirical evidence and data supporting the positive impact that these systems will have on improving safety, primarily because these systems have yet to penetrate the market fully. Currently results have only been drawn from experiments and simulations.

Second, there are uncertainties regarding the functional design and purpose of intelligent warning systems with regards social goals and market acceptance. Questions such as what preferences drivers have with regard to the level of automation and who has the ultimate responsibility in driving and making decisions (the driver or the ADAS) are pertinent issues that need to be addressed.

Third and last, the issue of liability is becoming increasingly important. Liability surrounding the use of intelligent warning systems is a major concern, especially in a litigious country like the United States [89]. Intelligent warning systems in general require a high level of interaction with the driver, a main aspect of which is the presentation of alerting information. Thus, human-centered design and a transparent human-machine interface are essential. Nevertheless, standards regarding a transparent and user-centered interface design have yet to be established. Consequently, without the presence of clear standards and regulations, there may be uncertainties with regard to liability and responsibility when accidents occur as a result of using the warning systems. In other words, who will be responsible – driving consumers, the automobile manufacturers or the warning systems equipment manufacturers when accidents occur? If there are clear standards for the automotive and equipment manufacturers, then it may be easier to partition responsibilities in the courts. Nevertheless, the issue of liability may still arise even if there are clear standards, particularly for cases where the intelligent warning systems that take partial control of the vehicles. Thus, the level of automation and control of these systems are engineering design, policy and social decisions that carry huge liability implications.

Implicitly connected with these three main institutional concerns is the setting of minimum standards and regulations. The important questions regarding *if* there should be minimum safety standards and *what* these standards should be, are questions to be answered not just by the engineers designing the warning systems, but also by the other major stakeholders who will be most affected by the outcome of the safety standards and regulations. These main stakeholders are the government regulatory agencies, automotive manufacturers, and the consuming public. Standards may affect the automotive manufacturers in terms of their innovation process and how the emerging technology develops, the consuming public in terms of market acceptance and penetration of these technologies and all three stakeholders when the benefits and costs of the emerging technology shift from one stakeholder to the other. Other stakeholders who may have a role in the decision-making process include the judicial and legislative parties, international organizations such as the International Standards Organization (ISO) and the Society of Automotive Engineers (SAE), insurance companies as well as component suppliers.

Before exploring what existing standards and regulations already exist for these intelligent driver warning systems, it helps to have a framework to understand why and how policy tools such as safety standards and regulations help in achieving safety, and a finer distinction between standards and regulations as well as that between the different types of safety standards will be distinguished. Second, different aspects of safety of intelligent warning systems will be presented so as to understand the kind of safety that the standards should be ensuring. Finally, existing standards and regulations of intelligent driver warning systems will be discussed.

2.3.1 Policy Tools to Achieve Safety Levels

2.3.1.1 The Three "E"s: Engineering, Enforcement and Education

There are three common approaches or policy tools that are used to overcome human error, improve safety levels or to reduce injuries in any type of complex system, including automobile safety [90, 91]. These three approaches are:

I. *"Engineering" or Technology Solutions* – These solutions are engineering and technology solutions that provide automatic and direct solutions, with minimal participation of the users. Examples of direct technology solutions designed to improve automobile safety levels include crash prevention technologies such as intelligent driver warning systems and crashworthiness technologies such as Antilock Braking Systems (ABS) and air bags.

II. *"Enforcement" or Judicial Solutions* – These solutions are regulations and enforcements designed to change people's behaviors so as to bring about increased safety. An example is mandatory seat belt laws, which together with a system of fines and penalties, discourage certain behaviors (i.e., not using the seat belts) and encourage other behaviors (i.e., using the seat belts). Regulations and enforcements can generally be further split into ex-ante/pre-activity regulations and ex-post/post-activity regulations:

    a. *Ex-ante regulations or "Regulations of Safety"* – These regulations are enforced before the technology is introduced and are direct ways to change people's behaviors. An example is the regulation of mandatory seat belt laws. In that case, people had to change their behavior to buckle up because of the enforced legislation. Another regulation is one that states that all vehicles must have air bags (as of 1998). In this case, the manufacturers had to ensure that their vehicle fleet met this regulation and thus, a behavioral change of the manufacturers was induced.

    b. *Ex-post regulations or "Liability of Harm"* – These regulations are enforced after the technology is introduced and are often indirect means to change people's behavior. For example, there were no regulations with regard to air bag installations in vehicles when they were initially introduced. Instead, liability cases ensured that manufacturers conducted sufficient research into air bags before releasing them into their vehicle fleet. Thus, liability of harm was an indirect regulatory solution to bring about behavioral change of the manufacturers to conduct more research in order to ensure the development of a safe technology product.

III. *"Education" or Social Solutions* – These are methods to persuade the user/public to change their behavior "voluntarily" by influencing them. Another term may be "moral suasion" which is a persuasion tactic used to influence and pressure (but not force) people to adhere to a certain behavior or policy. Unlike the previous judicial solution which forces a mandatory change of behavior by enforcing regulations, this indirect method of moral suasion influences a change in behavior through incentives. Incentives encourage a change of behavior since people will want to increase their total utility and benefit from the incentives. These incentives could be intangible or tangible. Examples of intangible incentives are the increased safety levels that are derived from the use of seat belts. The public could be educated through campaigns (both publicly and privately funded) on these safety benefits and since survival during a crash is generally perceived to have a higher utility than death, this intangible incentive can be used to persuade people to use their seat belts. Examples of tangible incentives are the economic incentives that are provided to encourage drivers to wear seat belts. For example, insurance premiums could be designed to be lower if drivers wear seat belts during a crash.

In general, the first approach of ensuring safety by using technology and automatic protection is the most effective and the third approach of moral suasion is the least effective. The main reason is because with automatic technology protection, there is little need to rely on driver participation, whereas the last approach depends mostly on drivers to change their behavior in order for the approach to be effective [90]. For example, seat belts have been shown to be highly effective in reducing serious injuries from automobile accidents from studies conducted in the 1960s. Nevertheless, mean seat belt usage was estimated at only 14.1% in 1978 and best estimates were still hovering around 20% for 1981 [92]. Even in 2005, the average national seat belt usage was estimated at 82%, with rates ranging from 60.8% in Mississippi to 95.3% in Hawaii [93]. These low utilization rates were in spite of both government-sponsored and private campaigns to educate the user population on the benefits of using seat belts. Thus, the method of suasion to change the behavior of the public was not a very effective policy tool at attempting to improve road safety.

In conjunction with the first method, regulations and enforcements were also employed to change people's behaviors and to encourage them to wear seat belts. NHTSA mandated in the 1970s that the engine starter could only be activated if the seat belts were engaged. This law is an ex-ante regulation that was put in place to "force" a behavior change of drivers – it was mandatory to wear seat belts in order to start the car! However, due to widespread unpopularity, Congress overruled this law. In its place, NHTSA passed mandatory seat belt laws for all states, which is another ex-ante regulation. However, even this second method of regulations and enforcements could not reach the desired improved safety levels for a variety of reasons. First, there was a need for a system of fines, penalties and resources to effectively enforce these laws. Second, in the U.S., there was considerably more opposition to government policies that attempted to regulate the behaviors of individuals as compared to Europe where mandatory seat belt laws were more effective. Third, economic research has suggested that people tend to compensate for the increase in safety (when using seat belts, for example) by engaging in more risky behavior. According to Peltzman, safety is an economic good (just like time) that people use to trade to increase their overall utility [94]. This phenomenon is known as risk homeostasis or behavioral compensation [95]. Thus, for these reasons, the second method of regulatory enforcements to change people's behavior in order to improve safety levels is often not very effective.

As a result, another more direct solution was needed and technology was developed to increase safety *without* the participation of drivers. The technology was air bags, which was pushed as a replacement for seat belts[1]. In 1977, the Federal Motor Vehicle Safety Standard (FMVSS) §208 required that air bags must ensure the safety of unrestrained front seat occupants. Thus, this standard reflected the beliefs of the decision and policy makers that drivers could not be relied on (either through soft measures such as public education or hard measures such as law enforcements) to wear their seat belts. As a result, a technology solution was designed to ensure that these drivers would nonetheless still be safe [96]. The development of air bags and air bags standards will be further explored in Chapter 4.

Knowing the various levels of policy approaches can help in understanding existing safety standards and regulations for intelligent driver warning systems and what policy approaches may be suitable. However, differences between standards and regulations should first be distinguished.

2.3.1.2 Safety Standards and Safety Regulations

There is a subtle distinction regarding the use of the word "standards" as opposed to "regulations" in the context of the policy framework outlined in the preceding section. In this thesis, a finer distinction is made. Standards correspond to the first policy approach of using "engineering" or technological systems to help improve safety levels. An example of a safety standard is that all air bags must ensure survival safety of occupants during a frontal collision at 30 mph. On the other hand, regulations correspond to the second policy approach of "enforcements" and laws. An example of a regulation is that all vehicles must be installed with airbags starting from 1998. See Table 3 for more

---

[1] When air bags were first conceptualized in the 1950s, they were developed to replace seat belts. However, we know today that air bags are more effective when used in conjunction with a seat belt.

examples. Thus, both standards and regulations are safety-related but the distinction lies in the different policy approaches to which they correspond ("Engineering" vs. "Enforcements").

Table 3: Distinctions between Standards and Regulations for the various safety devices in vehicles [97].

	Safety Standards (Correspond to engineering or technology solutions)	**Safety Regulations** (Correspond to "Enforcement" or judicial solutions)
Seat Belts	Fastened seat belts with lap and shoulder portions must meet crash test requirements at 30 mph.	Lap and shoulder seat belts must be installed at every forward facing and outboard designated seating position.
Air Bags	Air bags must meet crash test requirements at 30 mph.	Air bags must be installed in all vehicles starting from 1998.
Intelligent Warning Systems[2]	All warnings from FCWS must be auditory and all warnings from LDWS must be haptic.	All vehicles have an integrated system of ACC and LDWS installed.

2.3.1.3 Design Standards and Performance Standards

Safety standards can be further differentiated into two general categories as follows:

- *Performance standards* specify a minimum level of performance that must be met while the system or device (e.g., intelligent driver warning systems) is being used. Thus, performance standards are technical standards used to guarantee a minimum safety level [24, 98]. Examples include performance requirements during automotive certification for air bags and brakes [97]. It is worth noting that because performance standards are *performance*-based and technology-independent, they do not limit innovation since manufacturers have flexibility and incentives to decide on the optimal way to achieve the performance level with the least cost.

- *Design standards* include the physical aspects of the system, including factors such as alert modality and interface layout and location. As design standards are *prescription*-based (i.e., they are based on pre-specified procedures or approaches), they are technology-dependent to an extent, and hence, may stifle innovation. For example, confining the physical location of a particular control input limits the manufacturers in the design of a warning system, which may hamper innovation.

---

[2] Since there are no standards or regulations for these systems yet, these are illustrative examples.

Performance standards are generally more common than design standards in the automotive industry, as seen in the plethora of crashworthiness standards including performance requirements of brakes and air bags [97]. Distinguishing between the two main types of safety standards can help answer the question about *what* minimum safety standards should be applicable to the intelligent warning systems, and in particular, if performance-based and prescription-based standards should be used.

2.3.1.4 Standards and Standardization

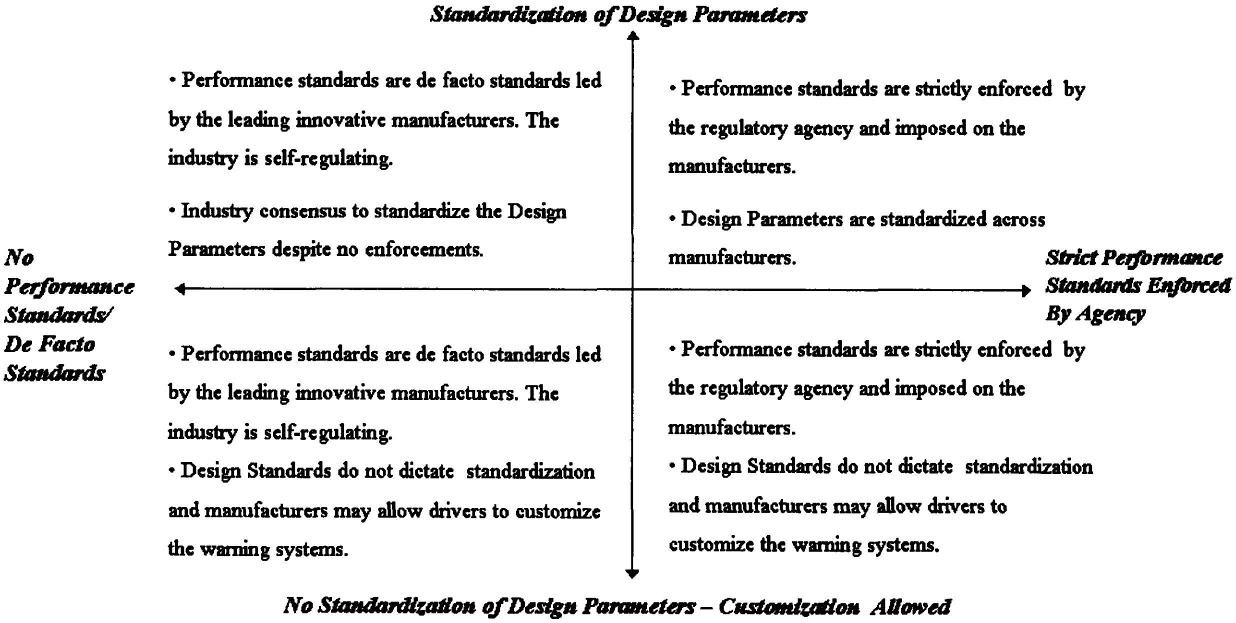
As illustrated in the preceding sections, there is a spectrum of different policy options, including standards and regulations that can be used to address the human factors problems that may arise from the use of multiple intelligent driver warning systems. In particular, the two types of standards, performance and design standards, can each vary along a particular dimension. One dimension is the degree of enforcement of the standards by the regulatory agency, which corresponds to performance standards. Another dimension is the degree of standardization, which corresponds to design standards.

Performance Standards and Degree of Enforcement:

Performance standards can vary along the dimension with regard to the degree of enforcement of the standards by a regulatory agency. On one end of the spectrum is the presence of strict standards and on the other end is the absence of any enforced standards. However, the absence of enforced standards does not mean that manufacturers are free to do whatever they want. Typically, because of the reactive judicial system (i.e., the judicial system that responds to the introduction of new technologies through product liability laws) in most developed societies, the industry typically self-regulates. Thus, even in the absence of strictly-enforced standards, "de facto" standards, which are shaped by the leading manufacturers to be informal standards, often emerge. Thus, the degree of enforcement will dictate whether the performance standards are strict enforced standards, or just de facto standards.

Design Standards and Degree of Standardization:

Design standards can vary along the dimension with regard to the degree of standardization of the various design parameters of the warning systems across manufacturers. On one end of the spectrum, these design parameters may be standardized across manufacturers. In other words, there will not be any variability in the design and interface of the warning systems because they are standardized, and drivers will experience the same intelligent warning systems regardless of which models lines of vehicles they drive. On the other end, there is no standardization of the design parameters, and manufacturers may be free to design the systems as they wish. Some manufacturers may even allow their users to customize and personalize the systems according to their preferences. Thus, since the warning systems are not standardized across manufacturers, they will vary considerably in terms of their design parameters, such as how alarms are presented.



- Performance standards are de facto standards led by the leading innovative manufacturers. The industry is self-regulating.
- Industry consensus to standardize the Design Parameters despite no enforcements.

- Performance standards are strictly enforced by the regulatory agency and imposed on the manufacturers.
- Design Parameters are standardized across manufacturers.

- Performance standards are de facto standards led by the leading innovative manufacturers. The industry is self-regulating.
- Design Standards do not dictate standardization and manufacturers may allow drivers to customize the warning systems.

- Performance standards are strictly enforced by the regulatory agency and imposed on the manufacturers.
- Design Standards do not dictate standardization and manufacturers may allow drivers to customize the warning systems.

Figure 5: Framework for the policy solutions for intelligent driver warning systems

Figure 5 shows how these two dimensions map out to performance and design standards. These two dimensions are continuous and not discrete. Thus, Figure 5 illustrates the extreme ends of the spectrum for both the dimensions.

2.3.1.5 Harmonization of Standards

In addition to these distinctions that have been made, a definition of another term, harmonization, is also necessary. Harmonization of standards is the adoption of unified and converging *international* standards, which could be either performance or design standards. Harmonization is different from standardization, in that harmonization refers to the standards that converge towards one beyond national boundaries, while standardization refers to the design of the warning systems that converge to one design. For example, within the United States, warning systems may be standardized across manufacturers because the regulatory agency may have design standards that strictly outline how the warning systems should be designed. Similarly, in Europe, there may be design standards that result in the standardization of warning systems there. However, even though the intelligent warning systems are standardized within the United States and within Europe, they may be very different because these design standards in the U.S. and in Europe are not harmonized.

Automobiles are highly regulated products for reasons including safety, energy conservation and environmental protection. Thus, while automobiles may be standardized within national boundaries, they may be very different across national boundaries. There has been a trend towards the international harmonization of vehicles standards. At the international level, the harmonization of vehicle standards and the co-ordination of research (not just safety-related) are advanced through the United Nations Economic Commission for Europe (UN-ECE). A specialized ECE body, the Working Party on the Construction of Vehicles (WP-29) has become a *de facto* global forum for the international harmonization of technical standards, including those of safety, for vehicles. WP-29 brings together regulators and representatives of manufacturers of vehicles and parts, consumers and other stakeholders from different countries [99].

2.3.2 Aspects of Safety of Intelligent Warning Systems

There are different aspects of "safety" when using ADAS and intelligent driver warning systems in the larger context of the traffic environment. Safety could be compromised in three major aspects, commonly classified as traffic system safety, usage safety and functional safety [100]. It is important to distinguish between these three aspects, because one policy approach (as outlined in the preceding section) may be used to address one aspect of safety, while another policy approach may be more suitable for another safety aspect. I now explain the three safety aspects in greater detail:

- *Traffic System Safety*: This safety aspect refers to safety issues arising from the traffic system as a whole (i.e., the entire complex operating system, including interactions between drivers and *other* vehicles in the roadway infrastructure). The focus is on issues such as the way that a particular warning system may influence the behavior of other users and alter the interaction between the driver, the vehicle, the roadway infrastructure and other road users. Thus, two examples of standards and regulations that may address this safety aspect are those that mandate that all drivers go through training before using a car installed with intelligent driver warning systems, as well as the regulations that modifies traffic laws to incorporate usage of the warning systems.

- *Usage Safety*: This safety aspect includes safety issues arising from the usage of the intelligent driver warning systems, thus focusing on the *interaction* between the operator (i.e., driver) and the machine (i.e., warning system). Key issues involve inappropriate design leading to driver confusion, driver overload or underload, distraction from driving, the lack of understanding of the capabilities of the warning systems leading to unjustified over- or under-reliance and mistrust of the warning systems. For example, standards and regulations may address usage safety by requiring that the driving performances of selected populations of drivers are not degraded when using the intelligent warning systems while driving.

- *Functional System Safety*: This safety aspect includes technical safety issues arising from both hardware and software design from the system itself. Note that the "system" here refers to the intelligent driver warning systems, which are different from the traffic system. The focus is on the technical reliability and robustness of the warning systems and their propensity towards malfunctions. Thus, standards and regulations may address functional system safety of the warning systems to ensure that, at least on a minimum level, the systems are robust and reliable.

2.3.3 Existing Safety Standards and Regulations for Intelligent Warning Systems

Safety standards on intelligent warning systems are non-existent today. There are no minimum safety standards that mandate that the warning systems must perform to a certain minimum requirement (performance-based), or that the warning systems must be designed a certain way (prescription-based). There are also presently no regulations such as those mandating that drivers understand and know how to use the driver assistance and warning systems, or that all vehicles must have these systems installed[3]. Thus, the questions of whether there should be any minimum standards at all, and if so, should these standards be standardized across manufacturers, are still open questions. I address these questions in Chapter 4.

---

[3] However, since the technology is still emerging now, it is more sensible to discuss standards first, then regulations, which typically tend to be decided later when the emerging technologies are already in the market.

2.4 Conclusions

Ensuring the safety of emerging technologies such as driver assistance and warning systems in automobiles is essential since these systems were designed to improve safety. In addition, the assurance of safety of products is also very important to both the public and the regulating authorities.

One way of improving both functional and usage safety is through continued research on intelligent warning systems, especially on how drivers perform in the presence of *multiple* warning systems. One design option is to use a master alert, instead of multiple distinct alerts for the multiple warning systems. As the number of warning systems in a vehicle increase, the use of a master alert may be advantageous since it will be synonymous with impending hazards and "danger!" However, the use of a master alert in warning systems for automobiles has not been sufficiently explored.

Another way to ensure the functional safety and especially the usage safety of these systems is by designing minimum safety standards. Such standards will assist in eliminating those systems that are not robust, unreliable and which may degrade drivers' performance. In addition, minimum pre-market safety standards also aid in informing the public that the particular assistance/warning systems being marketed are safe, since manufacturers have to meet the safety requirements before their products are allowed to market.

However, setting standards implies knowing *what* they should be. In addition, there are also uncertainties with regard to what a "safe" warning system is. For example, for a collision avoidance system, in terms of functional system safety, it is not straightforward to design one that is reliable, with an optimal balance between minimizing the number of false alarms and missing alarms. In terms of usage safety, it is not clear yet how the presence of multiple warning systems will affect the driver in terms of various human factors issues. Lastly, in terms of traffic system safety, it is even less clear how these warning systems will interact with each other in a complex traffic environment. In addition, there have even been doubts raised regarding the necessity of having safety standards and *if* there should be any standards at all.

As a result, there are no performance standards today to ensure the safety of the intelligent warning systems. Additionally, there are also no design standards that standardize the warning systems, especially in terms of the alerting strategy, modality presentation, and warning sensitivity. This lack of standards may not be a problem today, since such systems are not ubiquitous yet. However, as intelligent warning systems become increasingly pervasive in the future, the issue of standards and regulations will become more pertinent especially if these standards could help mitigate some of the technical issues that arise with the presence of multiple intelligent warning systems, such as confusion. These exact issues are problems in aviation today; a study conducted by the FAA on issues related to warning systems on aircraft found that inconsistencies in the alert utilization philosophies, lack of standardization and a rapid increase in the number of alarms in aircraft are major problems contributing to confusion of pilots and air traffic controllers [101, 102].

Even though there are no minimum standards today, manufacturers are already introducing these systems into higher-end luxury models. Thus currently, the main motivation ensuring that manufacturers are making their best efforts to develop safe warning systems is the judicial process. The burden of proof lies with manufacturers to show that their systems are indeed safe. This financial disincentive in litigation damages alone is sufficient to motivate manufacturers to conduct extensive tests and evaluations of their driver warning systems to an extent. However, this policy approach may not be ideal in the long run. Rather, safety standards may provide the answer to ensure that intelligent warning systems will improve road safety in the long run.

However, pre-market safety standards are hard to set because they generally provide little incentive for manufacturers to innovate. Innovation may be major radical shifts in technology, or just incremental adaptation of existing technologies. In the automotive industry, technological innovation is an especially significant determinant of economic growth and it is ideal to be a market leader through innovation [103, 104]. In addition, another reason why safety standards are hard to set is that the regulatory environment is very complex. Intelligent driver warning systems have not fully penetrated the market and thus, have unknown impacts concerning the issues regarding safety. The government has a role to guarantee minimum safety level to the public, yet government officials are not knowledgeable about the latest technology since the warning systems is an innovation-driven field where the technical experts are mostly the private manufacturers themselves, and for reasons of competition, do not divulge competitive secrets. As a result, nobody knows yet if there should be minimum standards and if so, what these standards should be [105]. This thesis thus aims to explore this question and consider the tradeoffs between various policy approaches, including setting minimum safety standards that may be able to mitigate the technical problems of confusion.

Chapter 3

Human Factors of Multiple Alarms

In this chapter, an experiment will be discussed that was conducted to investigate the effectiveness of several intelligent warning systems with multiple alarms. Details of the experiment will be presented, in addition to the results, discussions and limitations of the experiment. Finally, the human factors implications of using multiple intelligent warning systems in vehicles will be discussed.

3.1 Intelligent Driver Warning Systems Study

One goal of the thesis is to answer the following question: What are the human factors implications of using alarms with multiple meanings from multiple intelligent warning systems in automobiles? In particular, are there problems of confusion over the meaning of alarms, and, if so, what conditions will exacerbate this problem?

To address these issues, an experiment in a driving simulator was conducted. The primary factor of investigation was to compare the effectiveness of a single master alarm warning versus multiple distinct warnings for the different intelligent warning systems. A variety of different driver warning systems were chosen for investigation, including systems that signaled impending frontal (Forward Collision Warning System) and rear collisions (Following-Vehicle Fast Approach Warning System), as well as unintentional left and right lane departures (Lane Departure Warning System). Finally, driver performance under different reliability conditions of the warning systems was also investigated.

3.1.1 Apparatus

3.1.1.1 Simulator Hardware

The experiment was conducted on a fully instrumented, fixed-based driving simulator, a 2001 Volkswagen™ Beetle (Figure 6). The rearview mirror was provided through a projection on the front screen. Participants interfaced with the brake pedal, accelerator pedal and steering wheel (which provided force feedback for a degree of realism). The speedometer, turning signals, hazard lights, seat adjustments, air conditioning were fully functional. Auditory output, namely vehicular motor sounds and the pertinent alarm warnings were broadcasted through the in-car radio sound system. The virtual environment was projected onto a large wall-mounted 8 by 6 feet projector screen six feet in front of the driver. This provided an approximately 40° horizontal field of view. A secondary small screen connected to a number keypad was on the right side of the driver. Figure 7 illustrates the driving environment and the secondary screen.

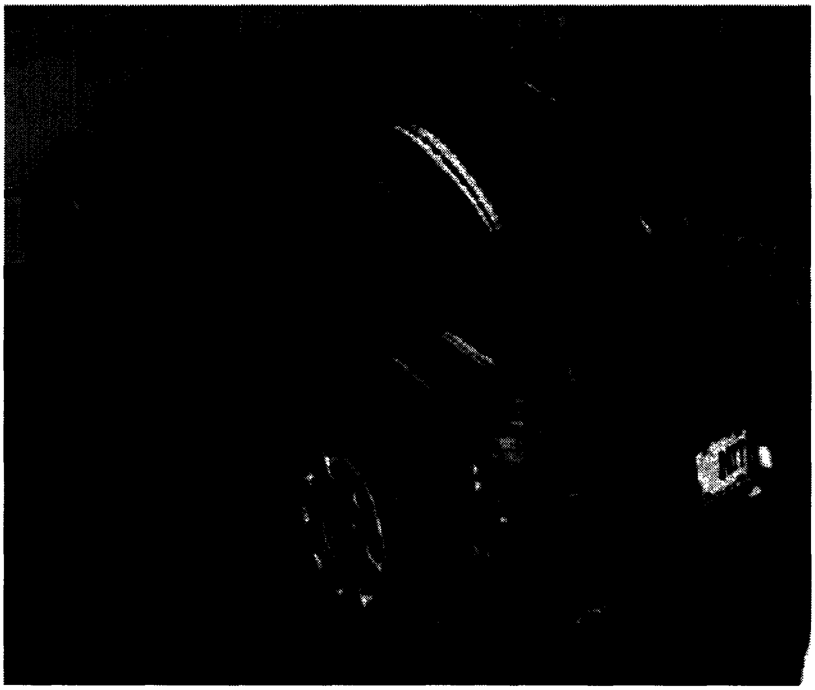


Figure 6: Exterior of Vehicle Simulator

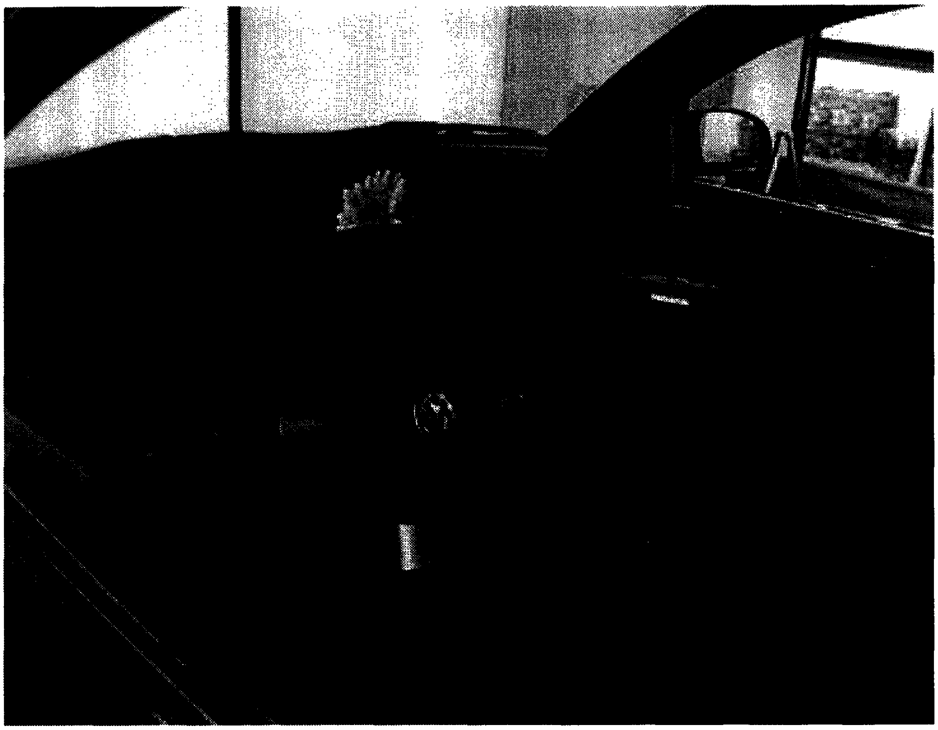


Figure 7: Interior of Vehicle Simulator

3.1.1.2 Simulator Software

A driving simulation test bed was developed using STISIM *Drive*™ Build 2.06.00 Simulation System developed by Systems Technology, Inc. Scenarios were built using the Scenario Definition Language (SDL) and modifications were made using the STISIM *Drive*™ Open Module code. The software running in the background recorded all of the participants' actions including the driving information, the vehicle's speed, steering angle, throttle and braking inputs.

3.1.2 Experimental Design

Three different factors of alarm alerting schemes (master and multiple alarms), driver warning systems (for signaling front and rear collisions and left and right lane departures), and warning reliability (high and low) were investigated. First, the impact of using a master alert as opposed to multiple alarms for the various intelligent warning systems was chosen to be the primary factor of investigation since as explained in Chapter 2, there may be advantages to using a master alert for multiple warning systems. This option has not been explored adequately in the driving domain.

Second, different warning systems signaling differing hazards were chosen which included frontal (Forward Collision Warning System, FCWS) and rear collisions (Following-Vehicle Fast

Approach Warning System, FVFA), as well as unintentional left and right lane departures (Lane Departure Warning System, LDW). These warning systems were chosen because they will potentially be among the earlier warning systems to be introduced into vehicles, as opposed to other systems like intersection collision avoidance systems, which are not likely to be introduced into the market in the near future. Thus these warning systems investigated both vehicle-to-vehicle and vehicle-to-infrastructure driver warning systems.

As explained in Section 2.1.1, current systems being investigated under the federal IVBSS initiative are Rear-End (or FCWS), Lane Change/Merge and Lane Departure Warning Systems, which is why the FCW and LDW systems were selected for this study. While the FVFA system is not currently planned for release in vehicles, unlike the FCWS and LDWS, it was chosen as a third warning system to complement and complete the fourth cardinal direction, the rear scene.

Third, the reliability of these warning systems was investigated because it is unlikely that any intelligent driver warning system on the market will be perfectly reliable. As explained in Chapter 2, there is a tradeoff to be made between false and missing alarms and thus, there will not be any warning systems without either false or missing alarms. Thus, two different reliability levels of the warning systems were investigated.

An experiment was conducted using a 2x4x2 mixed factorial design. These three factors will be explained in further detail in the following sub-sections.

3.1.2.1 Factor 1: Alarm Alerting Scheme

The first factor was the type of alarm alerting scheme: single master alarm or multiple alarms. This factor was a between-subjects factor. Half of the participants heard a single master alarm for all the different warnings, while the other half heard distinct alarms for each driving event (frontal and rear impending collisions, as well as potential left and right lane departures).

All the warning alerts in this study were tonal beeps provided by the Ford Motor Company to represent realistic warnings in use in cars today. For the single master alarm alerting scheme, participants heard a generic tonal beeping alarm from both in-car speakers for each of the driving events of front and rear collisions, left and right lane departures. For the multiple alarms alerting scheme, participants heard distinct alarms warning of the four different driving events. These alarms were as follows:

i) Frontal Collision Warning (FCW): a tonal beep consisting of a short phase difference, conveying a sense of urgency,

ii) Follow Vehicle Fast-Approach (FVFA) Warning: a tonal beep consisting of a longer phase difference,

iii) Left Lane-Departure Warning (LDW): an alert simulating a low frequency rumble strip from the left in-car speaker,

iv) Right Lane-Departure Warning (LDW): an alert identical to the Left Lane-Departure Warning, but presented through the right in-car speaker.

The sound levels of the warning tones were kept at a consistent level across participants. All participants indicated that they were able to hear and distinguish the alarms above the vehicular motor and background noise when they sounded. The media files for the sounds can be downloaded in the "Multimedia Resources" section on the Humans and Automation Lab website: http://halab.mit.edu.

3.1.2.2 Factor 2: Driver Warning Systems

The second factor was the driver warning systems or driving events, and there were four treatment levels: imminent frontal and rear collisions, and unintentional left and right lane departures. Even though the left and right lane departure warnings were, in reality, from the same driver warning system (i.e., LDWS), they were categorized as different treatment levels because the alarms were spatially located and because they warned of different driving/alarm events (i.e., departure to the left which required a steering correction to the right vs. departure to the right which required a steering correction to the left). This factor was a within-subjects factor, thus, every participant experienced all types of events (i.e., they heard an alarm for potential hazards in the four cardinal directions).

Participants experienced 2 testing scenarios. Each testing scenario contained an equal number of FCW, FVFA, Left LDW and Right LDW driving events, which were randomly interspersed in the roadway scenario.

3.1.2.3 Factor 3: Reliability of the Driver Warning Systems

The third factor investigated was the effect of warning reliabilities on driving performance. There were two treatment levels: high and low reliability across the different warning systems. This factor was a within-subject factor, and every subject experienced the two treatment levels. One scenario used highly reliable warning systems, while the other used warning systems with low reliability. The order in which participants experienced these two different scenarios was counterbalanced to reduce order effects.

The high reliability condition had a ratio of TP:FP =3:1 (true positive: false positive) while the low reliability condition had a ratio of TP:FP = 1:3. TP events were actual occurrences of the hazard for which the warning systems presented the appropriate alarms. TP events did not include user-triggered events. FP events occurred when an alarm sounded with no actual corresponding event. Thus, a TP is a "Hit", while a FP is a "False Alarm" (Table 2). In this experiment, missing alarms were not studied.

3.1.3 Scenario Design

This section gives a detailed explanation of the design of the scenarios, including the number of events per testing scenario and how events were ordered, the details on the triggering events of the various driver warning systems (i.e., for the four cardinal directions), the warning algorithms, and how they triggered and finally, an overview of the secondary task that all participants were asked to perform during the experiment.

3.1.3.1 Event Order

For each participant, there were two scenarios. Let A be the scenario with highly reliable warning systems and let B be the scenario with less reliable warning systems. In both scenarios A and B, participants drove through sections of rural highway, interspersed with dense city driving and suburban housing estates. There were traffic devices such as traffic lights, stop signs, as well as pedestrians (see Appendix B for pictures of the different driving environments). Participants drove through a two-way, two-lane road throughout the scenario, i.e., there was only one driving lane for the participant. If participants departed from the lane of travel, they would either go into the lane of oncoming traffic, or onto the shoulder of the road. The participants were not asked to make any turns.

For both scenarios A and B, participants experienced 32 driving events altogether. Since there were 4 different driver warning systems, there were 8 events (including TP and FP) per warning type per testing scenario. All 32 events were arranged in a random order for each scenario but all participants encountered the same order of events. This is because scenarios and the critical events have to be pre-programmed and cannot occur dynamically for each participant. Table 4 shows the breakdown of the events per scenario for the 2 different scenarios, A and B.

Table 4: Breakdown of TP and FP events for both Scenario A and Scenario B.

Reliability	**Types of Driver Warning Systems**				
	FCW	**FVFA**	**Left LDW**	**Right LDW**	**Total**
Scenario A: High Reliability, TP:FP = 3:1					
True Positives	6	6	6	6	24
False Positives	2	2	2	2	8
Total	8	8	8	8	32
Scenario B: Low Reliability, TP:FP = 1:3					
True Positives	2	2	2	2	8
False Positives	6	6	6	6	24
Total	8	8	8	8	32
Scenario order: A and B were counterbalanced across participants to account for order effects. TP and FP events of each driver warning systems were randomized per scenario.					

The scenarios were designed in such a way that the 32 critical events did not overlap in time, because this experiment was not investigating multiple threat situations. The events occurred approximately 30-45 seconds apart from each other, which ensured that human PRP is not a limiting factor in the study. Each scenario lasted approximately 12-15 minutes depending on how fast the participants were driving. However, scenario B tended to be shorter since there was a higher incidence of false alarms, as compared to scenario A where there were more true events, which sometimes caused collisions. Thus, scenario A had a longer average running time than scenario B (see Appendix C for more information on the exact order of the TP and FP events for both Scenarios A and B).

3.1.3.2 Triggering Events

Descriptions of how the TP events were triggered are provided here (see Appendix B for pictures of these triggering events).

- *Frontal Collision Warning* - There were four types of FCW triggering events:

  - A lead vehicle on the highway that braked suddenly. If it was detected that the brakes of the participants' car were applied, then the lead vehicle sped up and drove away. Otherwise, a collision occurred.

  - An oncoming vehicle on the highway passing another car, resulting in an impending head-on collision. The head-on incoming car swerved back into its own lane at the last second to avoid a collision, but still triggered the FCW warning. This is not a prototypical FCW event since many FCW suppress oncoming traffic. However, this particular triggering event was included to add more variability to the triggering events. In addition, the purpose of the experiment was to study how participants react to sudden critical events in the frontal scene. Since this oncoming vehicle was behind another car and then overtook at the last minute, it was expected that participants would not be expecting that event to occur.

  - A stationary-parked vehicle that pulled out from the side of the road into the driver's path. This vehicle was one of the many parked vehicles along the side of the road. This vehicle pulled out and appeared in the driver's lane of travel 3-5 seconds before impact. The vehicle sped up and drove away if the participant's brakes were applied. Thus, no collision occurred if the participants braked before contact.

  - A stationary-parked vehicle that backed out from a garage into the driver's path, and then moved forward into the garage again. The vehicle pulled out and appeared in the drivers' lane of travel 3-5 seconds before impact. The vehicle moved forward into the garage again when it was detected that the brakes were applied and there was no collision.

- *Follow Vehicle Fast-Approach* – There was one type of FVFA triggering event.

  - A following vehicle quickly approached the driver from the rear with a closing velocity of 50 feet/second or 34.1 mph. The rear vehicle approached and overtook on the driver's left when the two vehicles were within 2 feet of each other.

- *Lane Departure Warning* – There was one type of LDW triggering event for both the left and the right lane departure:
    - In this experiment, the LDW event was simulated by forcing a lane change maneuver on the drivers using a "windy" condition. In the real world, lane departure warnings are potentially useful for drivers who are inattentive, distracted or drowsy. However, such a scenario cannot be reliably reproduced during a controlled experimental test. Participants were told before the experiment that they would experience periodic wind gusts while driving. When an LDW-triggering "wind gust" occurred, participants experienced a gradual heading change of the vehicle and if they did not correct to bring the vehicle back to the lane of travel, there was subsequent lane departure either to the left lane or right shoulder.

3.1.3.3 Warning System Algorithm Design

For the longitudinal driver warning systems such as the FCW and the FVFA warning systems, the alarm triggered when the closing distance between the driver's vehicle and the lead/following vehicle was less than 200 feet apart, or 0.038 miles. Additionally, the warning systems would only trigger if the closing velocity between the two vehicles was more than 50 ft/sec or 34 mph. Assuming that drivers would drive at speeds between 45 mph and 65 mph on the driving scenarios, the alarms would sound approximately 1.05 sec to 3.04 sec before a potential collision.

For the FCWS, the alarms stopped when the driver decreased the closing velocity by braking or by swerving to avoid the impending frontal collision. For the FVFA system, the alarm stopped when the driver decreased the closing velocity by increasing the distance from the follow vehicle by accelerating or by swerving to avoid the impending collision. STISIM *Drive*™ allowed the brake, throttle and steering inputs to be calibrated. For example, the brake and throttle inputs were taken when the pedals were not depressed, and the inputs were taken again when the pedals were depressed fully. Since the inputs increased in a linear scale, a sharp braking and a sharp accelerating reaction was defined as times in which the pedals were depressed more than halfway down per simulation update cycle.

For the lateral control driver warning system, namely the LDWS, the alarm sounded only if the driver's vehicle was within 3 feet of the edge of the lane (i.e., the lane markings) and if the heading angle (or yaw angle) was more than 0.5 radians or 28.64 degrees. Lanes were 12 ft wide and vehicles were 6 ft wide in the scenarios. Additionally, the LDW did not sound if the turning signals were switched on. This mimicked how LDWS systems on the market today suppress alarms when turning signals are activated (Refer to Section 2.1.5.2). The left and right lane departure warnings stopped when the driver swerved back into the intended lane of travel The reaction time determined by how long it took for participants to perform a steering motion in the opposite direction from the lane departure.

3.1.3.4 The Secondary Task

Due to the popularity of telematics in vehicles such as in-vehicle navigation, communication and entertainment systems, attentional distraction is becoming an ever-increasing safety issue in actual driving. There have been numerous studies that have demonstrated degraded driver performance mobile phones, in-car navigational systems and entertainment systems are while driving [106].

In order to simulate the use of in-car telematics, a secondary task was designed to take driver's attention away from the roadway. A visual distraction task was chosen over an auditory distraction task (e.g., dialing a cell phone using voice recognition and conversing on the phone hands-free) because many telematics systems are primarily visual. Thus, it was necessary that the secondary task rely more on drivers' visual attention resources, requiring them to divide their attention between the driving roadway and the secondary task screen. That way, if the participants were not looking at the driving roadway when an alarm sounded, it would be possible to see if there was any difference in drivers' reaction times due to the different alarm alerting schemes. Moreover, a previous pilot study conducted with the presence/absence of a similar computational task found that drivers' reaction times significantly increased when they had to drive with the presence of a secondary task [107].

In this study, the secondary task that was performed throughout each scenario A and B, was simulated by a cognitive task, in which drivers were required to perform a computational task which was presented to their right on an internal LCD screen (Figure 8). A number string comprising of six zeros and one non-zero number was presented on the internal LCD screen. After adding the non-zero number and its position in the number string, participants entered the answer via the number keypad located just below the internal screen. For example, if the string displayed was "0 0 4 0 0 0 0", the correct answer was 4+3=7. The secondary task occurred at random intervals. Therefore, the secondary task could appear at the same time as a critical TP event. The purpose of the secondary task was to distract drivers visually so that they did not focus entirely on the frontal driving screen.

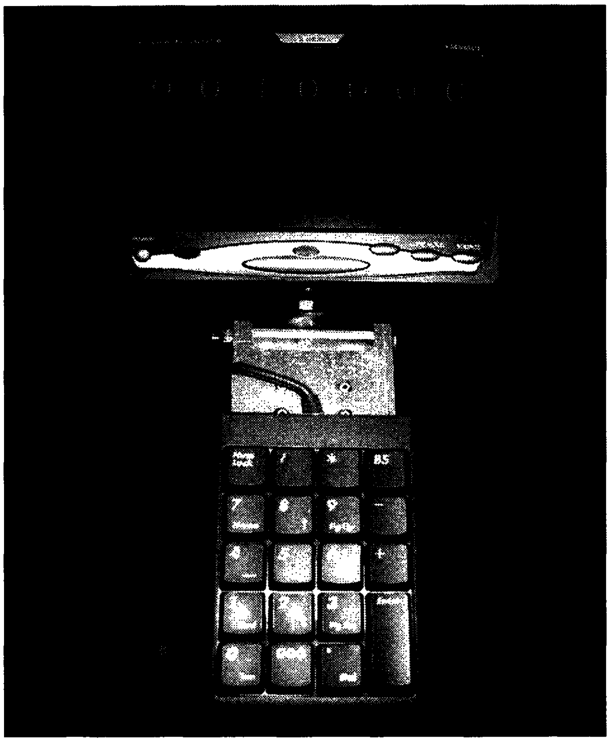


Figure 8: The Internal LCD Screen for the Secondary Task in the Vehicle Simulator

In addition, the secondary task was set up such that scoring was aggregated for the whole testing scenario on a percentage scale. Thus, no data were collected on how participants did on each computational task. Instead, the score on the secondary task represented the final score after the participants completed each testing scenarios. If participants did not respond within four seconds, the task would disappear and it would be counted as an incorrect answer.

3.1.4 Dependent Variables

In the study, both objective and subjective dependent variables (DV) were observed. Of the objective variables, there were two primary and two secondary DV. One of the primary dependent variables in the experiment was the reaction time to TP events. For a FCW event, the reaction time was the time taken to take a sharp braking action or sharp steering action to avoid a frontal collision. For an FVFA event, it was the time to depress the accelerator pedal or take evasive steering action. For an LDW event, it was the time to apply a sharp steering correction in a direction opposite of the lane departure. For the true positive events, the warning alarm did not stop until drivers took a corrective action or until the hazard went away.

The other primary dependent variable was the accuracy of response to the events. A response to a TP event was accurate if the correct corresponding action was taken to avoid the front or rear collision and lane departure (known as a "hit" in signal detection theory). A response to a FP event was accurate if the false alarm was correctly ignored and no corrective action was taken (known as "correct rejection" in signal detection theory or no response). False alarms sounded for approximately four seconds. Within this four-second time window, if participants made a significant change in the throttle, brake or steering input, then that reaction constituted an inaccurate response to a FP event. Otherwise, the participants' response was considered to be correct.

Even though previous research has indicated that speed and lane position/steering behavior are important indicators of drivers' responses to driver warning systems, these measures were not considered [108, 109]. According to the pilot study that was conducted before this experiment, it was noted that participants were always consistently speeding, possibly due to the lack of peripheral vision cues [107]. Thus, speed was not a good dependent variable in this experiment. As a result, participants were constantly reminded not to speed and to check the speedometer to ensure that they were driving below the speeding limit. Participants were also penalized more heavily for speeding (in terms of monetary bonus) than for arriving late (See Section 3.1.5 and Appendix F and H for more details). Even though lane position and steering behavior were not used as dependent variables, they were indirectly used to determine reaction time, e.g., when drivers took an evasive swerving action to avoid a hazard. These measures were not directly considered because it was not straightforward and clear what amount of steering input or lane position change constituted a reaction to the stimulus.

The two secondary DV under investigation in this study were the number of collisions and the score on the secondary task. The first measure, the number of collisions, reflected the research interests in the effectiveness of different types of driver warning systems in terms of driving safety. A collision or crash was defined when any of the following events occurred: a collision with another vehicle, pedestrians or roadway objects (e.g., construction cones, roadway dividers), or driving onto the shoulder of the road. The number of collisions is the total (combined) number of collisions that participants commit in the two testing scenarios. The second DV, secondary task score, was measured by the overall percentage score on the task. This second measure reflected the effects of driver warnings on secondary task performance.

Subjective DVs included the preferences and opinions of participants determined from a post-experiment survey (Appendix G).

3.1.5 Participants

Forty-eight licensed drivers participated in this experiment. Eight participants did not complete the experiment due to motion sickness from driving through the simulator scenarios. The 40 remaining participants (17 females and 23 males) were divided equally and randomly into the two treatment levels of alarm alerting scheme (i.e., half heard the master alarm, and the other half heard distinct alarms). All participants had at least one year of driving experience. Their ages ranged from 18 to 40 years, with the mean age of 25.8 years, and standard deviation of 5.43 years. All participants were MIT affiliates.

Participants received at least $15 for completing the experiment but had the potential of earning bonus of up to an extra $5 based on adherence to driving rules and regulations. See Appendix H for more details on how the performance bonus was calculated.

3.1.6 Experiment Procedure

The entire experiment lasted approximately 90 minutes per participant including filling out pre- and post-experiment surveys and driving through practice scenarios. Prior to starting the testing scenarios, all participants filled out an informed consent form (Appendix D), and a pre-experiment online survey (Appendix E*)*. The pre-experiment survey assessed participants' demographic data, driving history, tendencies for potential motion sickness as well as experience playing video games.

Next, participants were seated in the driving simulator and had time to familiarize themselves with the vehicle interface. Participants were told to drive as they normally would, obeying speed limits and traffic control devices such as stop signs and traffic lights. In order to reduce variability between participants, pre-recorded instructions were used (see Appendix F for a detailed transcript of the instructions). Every participant heard the same pre-recorded instructions.

The experiment consisted of three practice scenarios preceding two testing scenarios. Only daylight and dry road conditions were used but participants were told that it was a windy day and they may experience strong "wind gusts" that might blow them out of the lane. Participants were told that the warning systems were not perfectly reliable and that they would experience false alarms. However, they were not told specifically about the reliability level of the warning systems or the percentage of false alarms that they would experience. Participants were also not informed about the number of critical events that would occur throughout the scenarios.

For the three practice scenarios (15-20 minutes in total), participants acclimated to the simulator and encountered different critical events for the different driver warning systems, heard the alarms for the all events and also experienced false alarms, as well as practiced on the secondary task. During the first practice scenario, participants drove through a short highway stretch that did not have any traffic devices or other cars. After the first practice scenario, all participants were given a short quiz to test their recognition of the alarms. For example, one of the alarms was played at random and participants had to answer what they thought that alarm meant. If they did not recognize the alarms, they were told the answer, and they continued the quiz until they had all the alarms correctly identified. For participants who only had one single master alert, the quiz was rather straightforward. After this quiz, participants had two more practice scenarios to acclimatize to the simulator environment. During the second practice scenario, participants drove through an urban area with traffic devices (stop signs and traffic lights) and other cars in the roadway. After the second session, participants were asked to perform a secondary task while driving. Participants were instructed on how to perform the task and they were asked to perform four computations of the task without driving. Following that, they drove the third and last practice scenario while performing the secondary task.

Following the practice sessions were the two testing sessions (scenarios A and B). In each scenario, participants drove through approximately 42,000 feet of roadway consisting of urban, suburban and highway settings, and encountered the collision events presented in randomized order (see Appendix C for more details on the exact order of the triggering events). Each testing scenario lasted approximately between 12 – 15 minutes. Participants were required to drive while performing the secondary task. After participants completed the testing scenarios, they filled out a post-experiment survey (Appendix G).

3.2 Results

3.2.1 Reaction Time

One of the primary research questions in this study was how the different alarm alerting schemes, driver warning systems and system reliability affected drivers' reaction times for true positive events. Figure 9 provides an overview of how these factors affected reaction time.

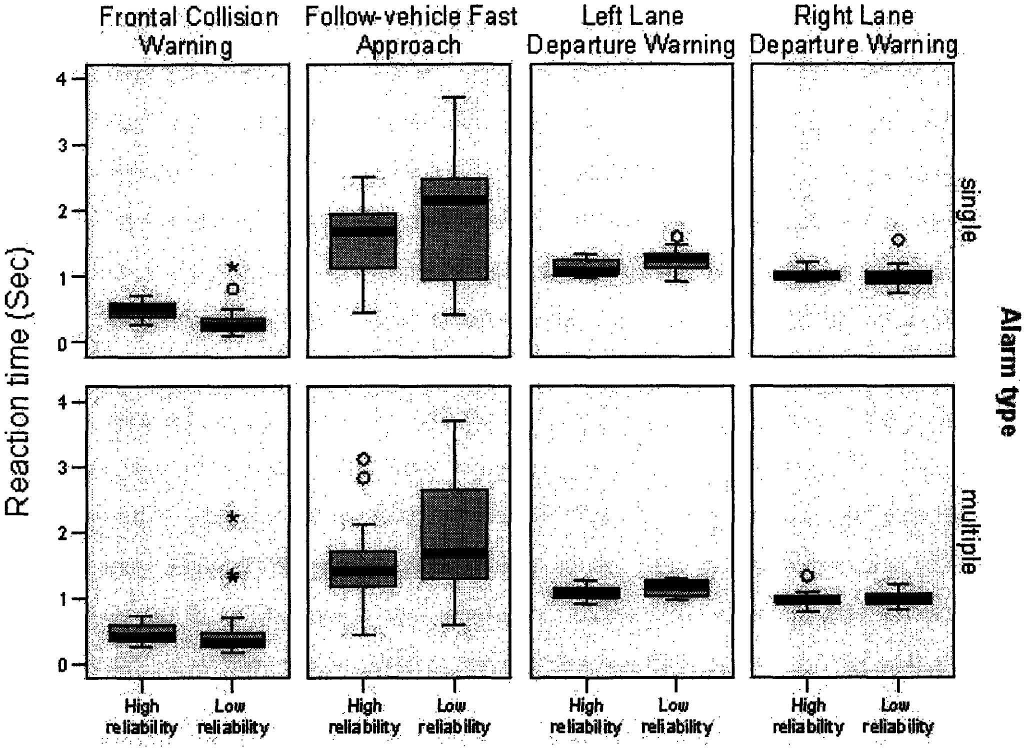


Figure 9: Reaction Time to True Positive Events across all Factor Levels

Further analysis was conducted by GLM repeated measures with alarm alerting scheme as a between-subjects factor, and driver warning systems and reliability as within-subjects factors (Appendix I). All data met normality and homogeneity assumptions with $\alpha = .05$. The alerting scheme factor (single/multiple alarms) was not a significant factor in affecting the TP reaction times (F(1, 38) = 0.00004, p = 0.995). Types of alarm alerting events (FCW/FVFA/LLDW/RLDW) and system warning reliabilities (high/low) factors were significant, (F(3, 114) = 91.244, p < .001) and (F(1, 38) = 9.694, p = .004), respectively. There was a significant interaction effect between types of warning systems and reliability (F(3, 114) = 8.559, p< .001) but no significance between alerting scheme and reliability.

Figure 10 demonstrates that reaction time to FCW alarms were the shortest, followed by that of the left and right LDW alarms. Reaction times to FVFA events show both a marked increase and a larger variance in performance. According to Bonferroni pairwise comparisons, the reaction times were significantly different for *all* pairings (p < .001) of the warning systems. From the interaction graph between the factors of driver warning systems and reliabilities (Figure 11), while reaction times were relatively constant across low and high reliabilities for the FCWS, Left and Right LDWS, the FVFA reaction times were significantly longer for the low reliability case as opposed to the high reliability condition.

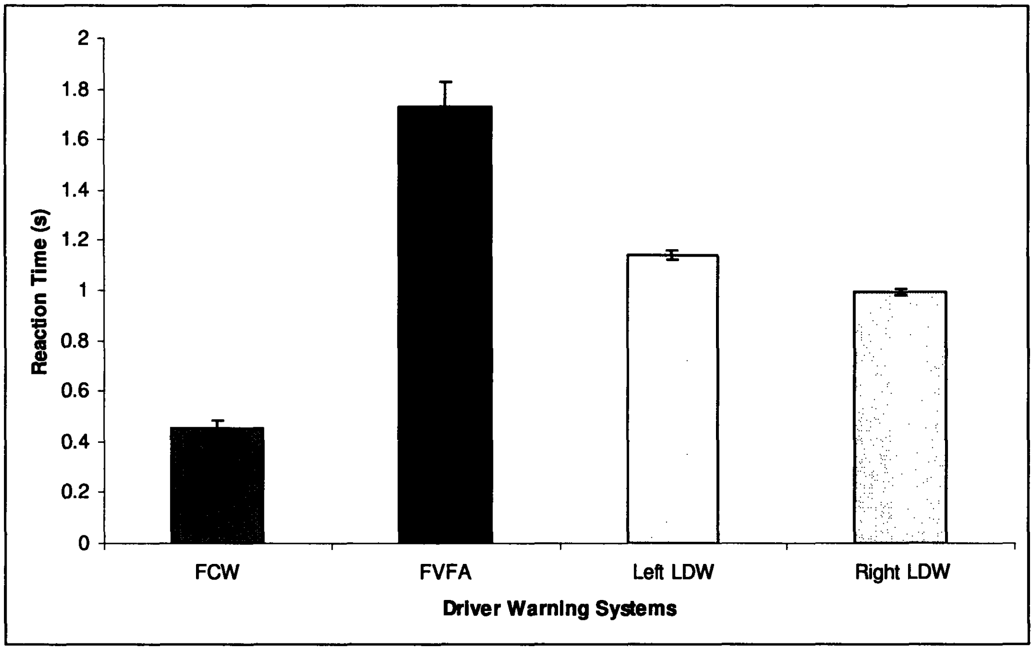


Figure 10: Pairwise Comparisons of Reaction Time

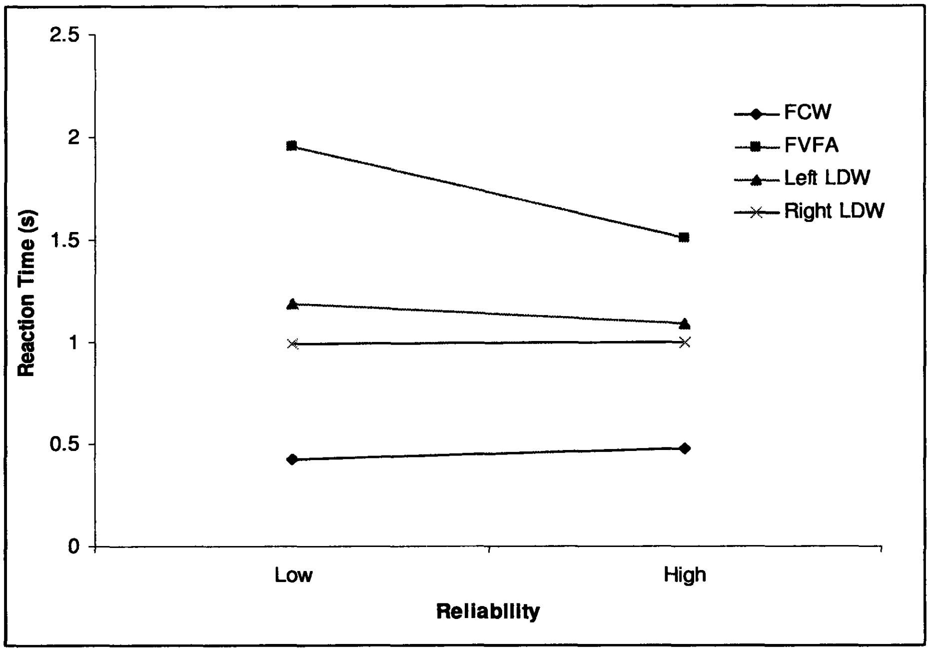


Figure 11: Interaction Effect— Driver Warning Systems X Reliability

3.2.2 Response Accuracy

Participants were generally accurate in determining the correct response to a given event, whether it be to intervene in the case of a true event or to take no action in the case of a false alarm. Over all test scenarios, 72% of the events were handled correctly (Table 5).

Table 5: Response Accuracy across all Factor Levels

		Correct Response Rate	Incorrect Response Rate	Missing Data Rate	Total events
Overall		72%	21%	7%	2480
Alarm Alerting Scheme	**Single**	72%	21%	7%	1240
	Multiple	72%	22%	6%	1240
Driver Warning Systems	**FCW**	73%	24%	3%	640
	FVFA	58%	22%	20%	640
	Left LDW	81%	18%	1%	600
	Right LDW	77%	21%	2%	600
Reliability	**Low**	58%	41%	1%	1240
	High	86%	1%	13%	1240

Because of the dichotomous nature of the accuracy dependent variable (either correct or incorrect given the two different TP:FP ratios), a non-parametric chi square test was used to examine the main factors. The results are very similar to the reaction time results, in that the multiple versus single alarm condition was not significant ($\chi^2 = .251$, df = 1, p = .616), but the different warning systems and reliability were significant ($\chi^2 = 14.121$, df =3, p=.003 and $\chi^2 = 548.0$, df = 1, $p < .001$ respectively). Figures 12 and 13 illustrate the main effects of driver warning systems and reliability (missing data not included) respectively. Participants were generally correct (either responding correctly to a true alarm or not responding to a false condition), but their error rate significantly increased when they had an unreliable system. Interestingly, Figure 12 shows that the error rates for responding to alerts in the front and rear quadrant were slightly higher than for the left and right. Figure 14 illustrates participants' responses for the different warning systems under both system reliabilities. This further demonstrates that the low reliability condition contributed to participants' errors in their initial responses. When only examining whether or not the responses to the false alarms were correct, the different driver warning systems were significant ($\chi^2 = 8.31$, df = 3, p = .04), but again the single vs. multiple alarm factor was not ($\chi^2 = .120$, df = 1, p = .729).

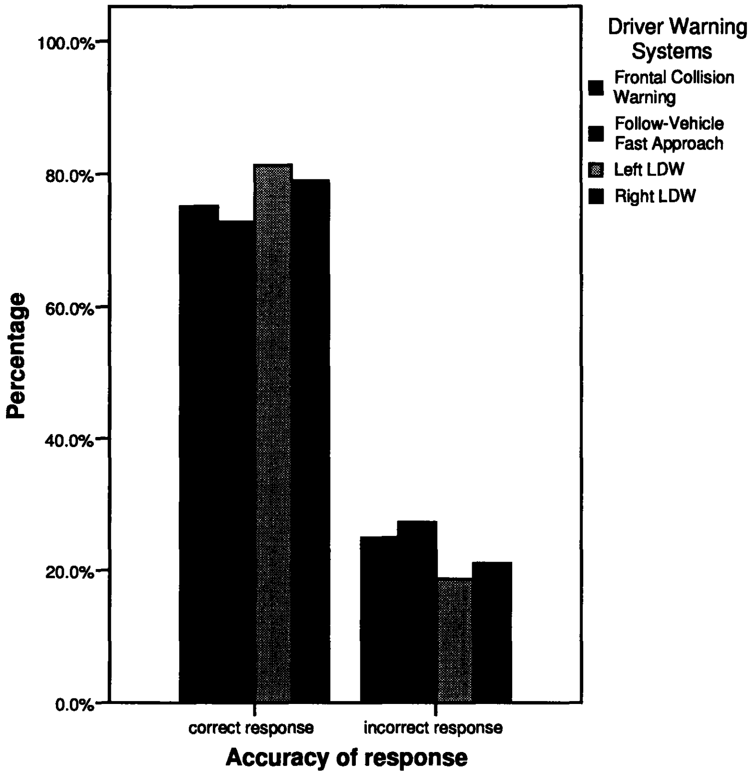


Figure 12: Response Accuracy— Main Effect of Driver Warning Systems

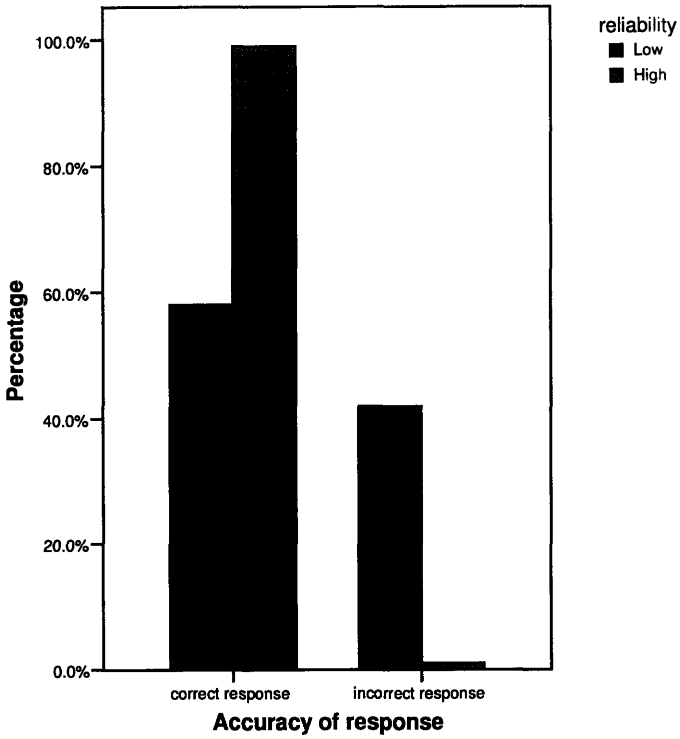


Figure 13: Response Accuracy —Main Effect of Reliability

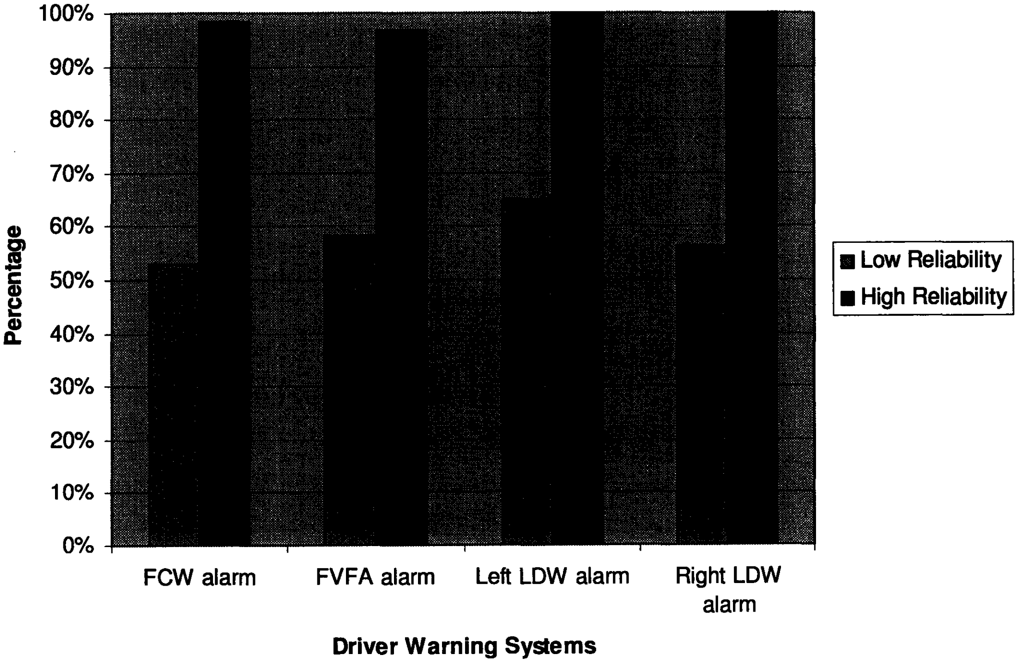


Figure 14: Response Accuracy – Interaction Effect

3.2.3 Number of Collisions

A non-parametric Mann-Whitney U test was selected to analyze the effect of alarm alerting scheme (single vs. multiple alarms) on the number of collisions because the alarm alerting scheme was a between-subjects factor and the frequency data failed the normality test. The reliability of driver warning system (within-subjects factor) did affect the number of collisions in the driving scenario according to the Non-Parametric Wilcoxon-Signed test ($Z = -2.696$, $p = .007$). This result is expected since high reliability has more true events and thus, the number of actual collisions will tend to be higher as well. However, the alarm alerting scheme did not affect the number of collisions in the driving scenario for both low and high reliability (in the high reliability testing scenario, Mann-Whitney $U = 190.5$, $p=.784$, while in the low reliability testing scenario, Mann-Whitney $U = 176$, $p=.392$.)

3.2.4 Secondary Task Performance

The secondary task score was based on the accuracy of the mental computational task, and was analyzed using non-parametric Mann-Whitney U test. This analysis showed that the alarm alerting scheme did not affect secondary task performance in the high reliability testing scenario (Mann-Whitney $U = 185.5$, $p=.693$), but it showed a main effect on secondary task performance in the low reliability testing scenario (Mann-Whitney $U = 128$, $p=.049$). Participants performed the secondary task better with the master alarm alerting scheme than with the multiple alarms alerting scheme when the reliability of driver warning system was low. Non-Parametric Wilcoxon-Signed test also indicated that reliability had a marginal significant effect on the secondary task ($Z = -1.798$, $p=.072$). Participants performed better on the secondary task in low reliability driving scenario than in high reliability driving scenario.

3.3 Discussion

This study yielded several important findings which will be discussed below in conjunction with survey responses obtained from the participants.

3.3.1 Alarm Alerting Scheme

One of the primary research questions in this thesis is how a master warning alerting scheme impacts driving performance as opposed to individual alarms. Results from this study showed that there was *no* significant difference in both drivers' reaction times and response accuracies under the different alarm alerting schemes, regardless of responses to TP or FP events. This is interesting, since it may mean that hearing either a master alarm or distinct alarms for different types of warning systems does not have a significant impact on the reaction time of drivers.

According to the post-experiment survey, 98% of participants reported that they were not confused by the alarm scheme. Moreover, according to the post survey questions asked to determine preference for type of alarms, 26% of the participants preferred the master alarm while 74% preferred having distinct alarms for the different driver warning systems. Out of the 74%, participants generally preferred auditory beeps as alarms for indicating left and right lane drift, and specific voice alerts (e.g. "front hazard", "rear hazard") for impending directional collisions (although verbal alerts were not used in this experiment, participants were given this option in the survey). Even though most people preferred a distinct warning for different systems and thought that distinct warnings would help them perform better, their reaction times and accuracy results showed otherwise. Thus, the objective results (i.e., reaction time and response accuracy) did not corroborate with their subjective preferences. This dissonance between users' preferences and their performance has been established for visual displays [110] and this study highlights that this discord can also be true for auditory displays.

Nevertheless, it should be noted that only aural alarms were used in the experiment and results may differ when combined with haptic and visual alerts or alarms. In addition, only three different driver warning systems (FCWS, FVFA and LDWS) were tested. In future implementations of warning systems in vehicles, there may be more systems such as intersection collision avoidance, blind spot detection systems, etc. Thus, even though warning confusion did not seem to occur in this study, as evidenced by both the objective performance results as well as by the participants' subjective answers to the post-experiment survey, the choice and design of the alarm alerting scheme may still be a significant factor when the number of ADAS and intelligent driver warning systems in vehicles increases.

3.3.2 Driver Warning Systems

There was a significant statistical difference in drivers' reaction times to the different driving true (TP) events. Reaction times to the FCW events were the shortest, while those to the Left and Right LDW were about the same. This is expected, since participants' attention was focused mainly on the front visual scene. An impending frontal collision elicited a quick reaction time on the order of 0.5 seconds. However, lane drifts did not have this inherent connotation of urgency associated with it, especially if participants were driving on an empty highway. Thus, reaction times to the left and right LDWS were about the same, but were both longer as compared to reaction times for the FCWS.

The largest reaction times occurred in the FVFA condition. Reaction times were much longer for responses to a potential rear collision for a variety of reasons. First, the delay may be caused by attention allocation. Participants directed most of their attention resources to the forward visual scene and the secondary task, rather the image in the rear view mirror. In addition, when participants heard the FVFA alarm, they needed to predict the potential behavior of the rear car. Thus, participants took longer to decide if the follow-vehicle was indeed closing in on their car or if it was just a false alarm, and respond accordingly.

As for subjective evaluations, 37% of the participants felt that the FCW alarms offered a timely warning in alerting them to impending collisions, as compared to a much higher 79% and 74% for the FVFA and LDW alarms respectively (Table 6). The forward collision hazard may have been more obvious to participants since their attention was focused more on the frontal visual scene and therefore, the FCW alarm seemed less useful to them. Alternatively, this difference between subjective preferences for frontal and rear collision warnings as well as the difference in objective reaction times may be due to the desire to cognitively offload the rearview monitoring task, especially since participants were distracted. Because potential critical events in the rear require an extra step of predicting what the following vehicle may do, as well as additional monitoring, participants tended to shed the rear-view monitoring task when distracted. This result suggests that for events not taking place in the frontal view, drivers need warning devices to assist in enhancing their situation awareness.

Table 6: Subjective Evaluation of Helpfulness of Alarms

Were alarms helpful in:	Yes	No
Avoiding a Frontal Collision	37%	63%
Avoiding a Rear Collision	79%	21%
Keeping in own lane	74%	26%

3.3.3 Reliability of the Driver Warning Systems

There was a significant difference in drivers' reaction times under different system reliabilities. However, this effect must be evaluated in light of the significant statistical interaction. As illustrated in Figure 11, the difference in system reliability primarily affected only the FVFA condition. Under this condition, participants' TP reaction times were shorter for the high reliability condition as compared to the low. This was generally expected under all conditions but only demonstrated under the FVFA condition. Since the rear quadrant events were more difficult to detect and correct for, the addition of an unreliable system caused participants to delay decisions to brake even further.

While there is a small effect of reliability for participants' reaction times, there is a much more significant difference in accuracy of responses to the different reliability levels. Responses to the highly reliable system were much more accurate than for the less reliable system. According to Figure 14, when the reliability level was high, there was essentially no difference between accuracy responses for the different warning systems, and when it was low, the correct responses to the different alarms dropped dramatically. Furthermore, correct rejection of false alarms dropped from 98.3% for a system with high reliability (25% false alarm rate) to 60.7% for the system with low reliability (75% false alarm rate). Thus, driving performances were negatively influenced as the reliability of the warning systems dropped.

On the whole, the rates for responding accurately were generally high (Table 5). Most of the inaccuracies came from responses to the false warnings, which were particularly problematic in the low reliability condition. While the LDW system appeared to produce the best performance under low reliability, the remaining systems were between 50-60% in terms of accuracy performance. The significant drop of error rate across all four warning systems from low to high clearly demonstrates that reliability of alerting systems is critical in achieving superior human performance.

In terms of subjective assessments, according to post-experiment survey results (Appendix G), 33% of participants felt that the alarms were an annoyance; 27% felt stressed by the alarms, and 22% felt that the alarms were distracting and adversely affected their driving. These results illustrate that even if the participants did well in terms of driving performance, many perceived the alarms negatively. This perception could have been, in part, a function of the nature of the experiments during which alarms constantly sounded, especially in the low reliability test sessions.

A high percentage of participants reported on the post-experiment survey that they knew when an alarm was a false one (Table 7). Yet a consistently lower percentage of participants correctly rejected a false alarm by not responding. This illustrates that even though participants knew or thought that an alarm was false, they still responded. One reason might be that when the participant heard an alarm, it was instinctive to respond. Furthermore this could be a "better-be-safe-than-sorry" riskaverse attitude because no negative costs were incurred if they responded to a false alarm since there was no penalty for responding to a false alarm. This result also illustrates that there is a bias in subjective assessment of performance and that the participants tended to overestimate their performance, which is a well-established phenomenon [111].

Table 7: Subjective and Objective Measures of False Alarm Awareness

Did participants know a False Alarm when they heard one?	Subjective Yes – Based on Survey Questions	Objective Yes – Based on Accuracy of Responses to FP events
FCW alarm	92%	48.8%
FVFA alarm	88%	51.9%
Left LDW alarm	82%	66.3%
Right LDW alarm	88%	52.5%

3.3.4 Secondary Task Performance

The secondary distraction task was intended to serve as a surrogate for visually and cognitively demanding in-vehicle tasks such as navigation, communication and entertainment devices. While of statistically marginal significance, it appears that participants performed slightly better on the secondary task in the unreliable systems condition. This suggests that participants were aware that the false alarm rate was high and thus directed more attention towards better performance on the secondary task. Since the TP condition was usually not imminent in the low reliability condition, participants adjusted their strategy accordingly and completed the secondary task. In the high reliability condition, participants appropriately ignored the secondary task to concentrate on the more frequently occurring TP hazards.

3.4 Limitations

These experimental results must be verified in more realistic settings since they are constrained by the test methods and simulator used. These results are subject to the following limitations, as will be illustrated in this section.

3.4.1 Field-of-View

The field-of-view was only limited to the front, and no side-mirrors were provided. This limitation caused some serious problems in the driving simulation including a lack of peripheral cues and an inability to detect blind spots. As a result, many participants drove at higher speeds than they thought they were. In addition, when the following vehicle in the FVFA triggering event was overtaking the participants' vehicle on the left, participants could not see where it was. This limitation was not a serious one in this experiment as participants always knew when the following car was behind their vehicle (in part due to the warning of the FVFA system which caught their attention). Thus, participants knew when the following car was overtaking them. However, if the field-of-view could be expanded to include side mirrors and blind spot as well, the scenarios could then be changed to a multiple lanes scenario (instead of two-way, two-lane roads), and other warning systems like the Blind Spot Detection Systems could be investigated as well.

3.4.2 Degree of Realism

The simulator was not very realistic in a few ways. First, it is in a laboratory setting and not in the real world. Participants know that they are participating in an experiment and hence may be more vigilant than normal. Second, there was a high density of alarms in a short period of testing time. As previously discussed, true positive critical events in the real world occur with a much lower base rate. Thus, for participants to hear 32 alarms in 15 minutes (32 TP and FP events per testing scenario) is unnatural. Third, the left and right lane departures were triggered by simulating a strong wind gust blowing the car out of the traveling lane. However, unlike in reality, no haptic feedback was provided via car movement when a windy event occurred. Additionally, some participants also became confused because the trees did not move during the windy events. Thus, if these factors could be improved in future laboratory simulation, then the degree of realism of using wind gusts to simulate lane departures would be increased.

3.4.3 Follow-Vehicle Fast Approach Missing Data

It was difficult to automatically detect reaction times for the FVFA alarm due to lack of sensitivity in the hardware and software, which led to missing data. According to Table 5, there was 20% of missing data for the reaction times to the FVFA events, as compared to 1% - 3% of missing data for the other three warning systems. The main reason for this was because of the way the warning system algorithm was designed. As previously explained, reaction time was defined as the difference in time from the onset of the alarm sounding to the time an evasive response was detected. In the case of FVFA warning events, this evasive response was either a sharp steering action to move to the side of the road to allow the following vehicle to overtake, or a sharp depression of the throttle to increase speed and separation distance between the vehicles. The missing data occurred when drivers were already depressing the throttle pedal fully when the alarm sounded. In other words, drivers perceived the following vehicle as a potential hazard *before* the alarm warning sounded. Since participants were already fully depressing the pedals and if these participants did not perform a steering action, then there was no way the algorithm was able to capture their reaction time. Thus, in future studies, this data collection method and the algorithm to capture the drivers' reaction times to the alarms should be further studied and refined.

3.5 Conclusions

An important finding from this study is that even though participants *preferred* distinct alarms for different driver warning systems, their objective performance showed *no* difference in both reaction times and accuracy of responses regardless of whether a single master alarm or multiple distinct alarms was used. That may mean that participants were able to discern, recognize and remember what the alarms meant, as there were few incorrect responses to the alarms. Thus, regardless of whether participants heard a single master alarm or multiple distinct alarms, they were able to both respond accurately and in a timely fashion to avoid the hazards. However, this finding was found under the particular experimental settings, and where only auditory alerts were used. In addition, the number of driver warning systems tested was limited to the FCW, FVFA and LDW warning systems. Nevertheless, this is an important finding, and if future studies find that driving performance is indeed truly unaffected regardless of alerting schemes and the number of alarms, then this finding may mean that there may not be any need for the design of the warning systems, in terms of alarm presentation, to be consistent across automotive manufacturers. In the extreme case scenario, manufacturers may even be able to customize the alerting schemes of driver warning systems to the customers' desires, or use a simple master alerting scheme for vehicles.

Furthermore, while not unexpected, the results demonstrate that low reliability can dramatically (and negatively) influence human performance. Even though drivers may not be confused by the alarms from the warning systems, they may still experience other negative emotions, including stress, annoyance and anxiety. Thus, these findings further highlight the need for the development of highly reliable intelligent warning systems. While intelligent driver warning systems can serve as an additional protection to drivers in times of urgent or emergent events, as demonstrated in this study, decreased system reliability can dramatically increase incorrect responses to these systems. If there is a high incidence of false alarms for intelligent warning systems, drivers might be better served by not having such aids at all.

This study served as an initial study seeking to address the gaps in the research of driver performance in the presence of multiple driver warning systems. However, these results were found in a laboratory setting and may not generalize to actual driving scenarios. One artifact of experimental studies such as this one is that participants experienced an unusually high incidence of potential collision events and lane departures in a compressed time period. Thus, participants are expecting the alerts to sound and assume a higher mental alert state in response to the test conditions. However, in reality the frequency of these critical events will be much lower for an average driver. In addition, since the warning alarms sounded every 30-45 seconds in the experiment, participants were more likely to be able to recognize and remember the meaning of the alarms. However, since TP events would be relatively rare occurrences in reality, whether drivers would know what these distinct alarms meant given sporadic usage still remains an open question. It is nonetheless encouraging that a single master alert appears to work as well as multiple alerts even in a laboratory setting. This might be explained by the fact that the driving context usually defines the nature of the hazard. A master alert associated with a lane departure, for example, will generally be interpreted as such when the driver perceives the vehicle's lane position and yaw angle. Similarly, a master alert for a forward collision threat will also generally become apparent once the driver focuses attention to the forward visual field and sees a vehicle or obstacle ahead.

Future studies should investigate more driver warning systems, examine multiple threat scenarios and investigate the effects of multi-modal warning alarms. Additionally, the collision avoidance systems and driver warning systems tested in this study were Level 2 ADAS (i.e., systems that aid drivers in recognizing a hazard and in providing judging for the criticality of the hazard). Future studies may also investigate effects of using Level 3 ADAS (i.e., active intelligent warning systems that intervene to take control and operate the vehicle in order to mitigate the hazard). Additionally, the secondary distraction task used in this experiment was a visual task that involved simple computational addition. Future studies may use an actual navigational tool as a distraction task (e.g., drivers having to navigate using GPS) to mimic what drivers may experience in reality.

Chapter 4

Safety Standards and Implications of Policy Decisions

The goal of the chapter is to answer the following question: Should there be minimum safety standards for intelligent warning systems in automobiles to mitigate possible human factors problems and to increase overall safety? If so, what should these safety standards be and what are the implications of the policy decision to enforce the safety standards?

As previously discussed, intelligent driver assistance and warning systems are technology solutions designed by engineers to help reduce the number of highway collisions and to improve overall road safety by preventing collisions. These intelligent warning systems can be either passive warning systems (i.e., Level 2 ADAS), that passively mitigate hazards by providing drivers only with warning alarms, or active warning systems (i.e., Level 3 ADAS), that actively intervene to mitigate hazards by taking over partial to full control of the vehicle. Previous focus on automotive safety has been on crashworthiness technologies to mitigate the severities of injuries during collisions. However, that focus is now shifting to developing intelligent crash avoidance and prevention technologies. Since intelligent warning systems are considered emerging technologies, there are many unanswered questions such as the large-scale effects and safety benefits of these technologies. One of these unknowns is how drivers will respond to intelligent driver warning systems especially during threat scenarios, and if safety levels will indeed be improved with the presence of these systems.

Intelligent warning systems technologies differ from traditional automotive technologies in that the critical component is the interaction between the humans and the systems. Unlike crashworthiness technologies which have minimal driver interaction, most intelligent driver warning systems depend on appropriate input from the drivers in order for the technologies to work as designed. Thus, if drivers become confused and do not take the appropriate response intended to avoid the hazard, then the systems have failed. In comparison, crashworthiness technologies fail when there are flaws in the product design, development or manufacturing process.

There are two broad solutions that can be used to address the human factors issues that arise due to the introduction of collision avoidance and warning systems into vehicles. First, technology can be developed to address these issues, such as more sensitive sensor systems or optimal alerting strategies for alarm presentation. Second, standards and regulations can also be made to provide solutions to these issues. For example, policy decisions such as the standardization of the driver warning interface may be able to mitigate problems of confusion for drivers. This may especially be important if inconsistencies in alarm utilization philosophies, lack of standardization, and a rapid increase in the number of alarms in vehicles all contribute to the problem of confusion, leading to driving degradation. However, setting safety standards includes knowing *what* the definition of a "safe" warning system is, *if* there should be minimum safety standards in the first place and, if so, *what* these standards should be.

This chapter will address these questions and explore the tradeoffs between various policy solutions. First, a case study will be presented on air bags technologies. This case study explores how standards and regulations for this older passive technology can inform the standards case for intelligent driver warning systems. Next, existing safety standards, or the lack thereof, for intelligent driver warning systems will be presented. The different policy solutions presented in Chapter 2 will be outlined again and following that, the major tradeoffs to these policy solutions will be explored. After exploring the tradeoffs to the different policy solutions, the question of whether there should be any minimum safety standards will be addressed, and finally, recommendations of *what* minimum safety standards should be and their implications will be given.

4.1 Case Study: Air Bags Standards and Regulations

In this section, a case study of the air bags technology is presented because it is a well-established automotive safety technology that has been recently developed, and it provides an illustration of how standards and regulations develop in conjunction with the introduction an emerging technology. Important lessons can be learned from how these standards of air bags were shaped and can be applied to intelligent driver warning systems.

4.1.1 Why Air Bags were Developed

In spite of different policy approaches such as "education" (e.g., campaigns) and "enforcement" of regulations (e.g., mandatory seat belt laws) used prior to the 1950s to improve road safety, driving habits did not change and the rising number of collisions indicated that another solution was needed. Instead of attempting to change and influence drivers' attitudes and behavior through social and judicial techniques, another more direct "engineering" or technological approach was warranted to compensate for the shortcomings of drivers. In particular, air bags were developed in the 1950s to mitigate the severity of injuries during a crash. Air bags were designed to compensate for irresponsible human actions (i.e., not using seat belts) by ensuring survival during crashes even for unrestrained occupants. Thus, air bag technologies sought to eliminate the need to rely on drivers to engage the safety restraint. Human responsibility was to be replaced with an engineering solution.

4.1.2 Resistance to Air Bag Technologies

Initially, when air bags were introduced during the 1960s, many resisted the technology, especially those in automobile companies. This was due to three major reasons [112]. First, air bags and other crashworthiness technologies represented a major foundational shift in automobile safety trends. Before the 1950s, automobile manufacturers only had to ensure that the control components of the vehicle (namely the brakes, throttle and steering) did not fail. Drivers were responsible for their own safety. The advent of interest in crashworthiness technologies such as air bags represented a radical shift that transferred responsibilities to automobile manufacturers in ensuring that vehicles were safe. Thus, there was resistance against the increase in liability that manufacturers would potentially face. Before, automobile manufacturers were only held liable if an accident was caused by a steering or braking failure that was directly due to a production fault. The introduction of air bags and other crashworthiness technologies meant that manufacturers could potentially be held liable regardless of whether the drivers were reckless or not, since they now had a responsibility in ensuring that cars could protect its occupants even during a crash. Second, air bags were extremely expensive and installing them in vehicles meant significant changes in the assembly lines. Third, there was the general attitude among automobile manufacturers that "safety doesn't sell."

However, by the 1990s, the resistance to air bag technologies had disappeared. Today, that has changed dramatically with manufacturers using safety as a huge innovation and selling factor (e.g., Mercedes-Benz, BMW, Infiniti, etc have installed LDWS and ACC in some model lines). There were three major reasons for this shift in viewpoints, which occurred approximately in the 1970s. First, the rapid development in sensors and microelectronics technologies made air bags more reliable, and manufacturers were thus more receptive to installing them. Second, there was an increase in public interest in safety devices, which helped convince manufacturers that safety could sell. Third, because of the increased interest in seat belts, NHTSA did not promulgate the impression that air bags were designed to *replace* seat belts, as originally thought. Tests showed that air bags were more effective when used together with seat belts. Thus, manufacturers were not entirely responsible for ensuring survival during crashes (i.e., with air bags); instead, drivers were also responsible and were expected to buckle up [112]. Thus, the liability of manufacturers was decreased.

4.1.3 Formation of NHTSA

Regulatory standards are typically established by a government agency and in the United States, NHTSA is the federal agency that has a legislative mandate under Title 49 of the U.S. Code, Chapter 301, Motor Vehicle Safety, to issue Federal Motor Vehicle Safety Standards (FMVSS) found in Part 571 [113]. The legislation (standards and regulations) of air bags was tied intrinsically with the creation of NHTSA itself, which was formed to regulate manufacturers at a time when the paradigm shift in thinking regarding the responsibilities of automobile manufacturers occurred. The National Traffic and Motor Vehicle Safety Act passed by Congress in 1966 led to the creation of NHTSA, whose role is to "establish appropriate Federal Motor Vehicle Safety Standards" that can "meet the need for vehicle safety" [114]. Thus, NHTSA is responsible for establishing and enforcing rules that would force manufacturers to build vehicles that could better avoid and withstand accidents. The creation of NHTSA was an effort to protect the common public good of safe automobile travel from both irresponsible drivers and irresponsible manufacturers by requiring that vehicles meet certain minimum levels of safety standards [112].

4.1.4 Market-Driven Innovation

As previously mentioned, by the 1990s, resistance to the air bag technology disappeared and air bags were installed widely in the vehicle fleets of various manufacturers. For example, in 1983, Mercedes-Benz was the only manufacturer to offer driver-side air bags in the United States; in 1989, only 3.2% of vehicles had air bags; in 1991, that number had risen to 33.2% and by 1994, driver-side air bags were standard equipment in 91% of vehicles [115, 116].

It may be postulated that air bags were installed so widely because of regulatory pressure from NHTSA. However, that was not the case, since NHTSA's regulations mandating all vehicles have air bags did not come into effect until 1998. Thus, since the air bags were installed as standard equipment *ahead* of the regulatory schedule, the significant driving force behind the use of air bags was market demand. Consumer behavior research showed that drivers were willing to pay for safety features such as air bags, especially in the larger-car market segments [115]. Predictably, air bags first appeared in large cars where the willingness to pay was the highest. As economies of scales brought manufacturing costs down, air bags began to appear in smaller-sized cars as well. Thus, it was not only regulatory pressure, but additionally, market demand factor also played a role in shaping the introduction of air bags as standard safety features into vehicles.

4.1.5 Air Bag Standards and Regulations

At the same time that manufacturers were developing air bag technologies, NHTSA was shaping the related safety standards and regulations. FMVSS Standard No. 208, called Occupant Crash Protection, is the frontal impact protection standard and regulation in the United States, whose purpose is to reduce the fatalities and severity of injuries to occupants involved in frontal crashes, which account for the majority of vehicle fatalities in the United States [97]. This standard includes air bags and specifies performance requirements for anthropomorphic test dummies seated in the front seats of passenger cars.

From 1969 through the 70s and 80s, NHTSA attempted to mandate air bags as standard equipment for all cars in the United States. However, as mentioned earlier, automakers were resistant because of liability and litigation costs. Thus, air bag regulations were not enacted until years later. Nevertheless, even though the regulations of air bags were not formally set in place, NHTSA did specify minimum safety standards for how air bags should perform (note: this is the difference between standards and regulations). Air bags were required to deploy in a 30 mph frontal barrier crash test with two belted and unbelted 50th percentile 5-ft-8, 167-lbs male dummies. NHTSA specified that the tests that ensured survival on the median male were only *minimum* requirements to judge the safety effectiveness of air bags; it was up to the manufacturers to exceed the requirement standards to ensure that air bags were safe for the whole spectrum of drivers, including smaller-stature female drivers and child occupants.

As air bags began to appear more widely in vehicles in the 1990s, an unanticipated consequence surfaced. By the mid 1990s, the number of deaths caused by air bags, specifically for out-of-position (OOP) occupants such as smaller-stature females and children began to rise sharply. NHTSA's Special Crash Investigation program concluded a total of 158 fatalities were caused by air bags as of April 2000, of which 92 were children, 60 were drivers, and 6 were adult passengers [117]. Research found that in order for air bags to be effectively deployed to ensure safety of the *unbelted* median male, a minimum inflation force was necessary. Consequently, this force proved fatal to smaller-stature occupants, who were often seated closer to the air bags when they deployed and for whom the air bags were causing more danger than safety. Not surprisingly, there was an increase in public outcry over the danger of airbags to these occupants. Thus, the public wanted the choice of deactivating air bags in their vehicles. Nevertheless, NHTSA, the automobile industry, and insurance and safety organizations knew the air bags did indeed save many lives and should not be completely abandoned as a technology. Between 1986 to March 2000, NHTSA estimated that air bags saved 5303 front seat occupants, including 4496 drivers and 807 right front passengers [117]. NHTSA also projected that the lives saved by air bags would increase even more if more people used seat belts during crashes. This is because some drivers stopped wearing seat belts, thinking that air bags were a replacement for seat belts. As a result, air bags indirectly caused some fatalities as well. Thus, while air bags did indeed save lives in high-speed crashes, they also caused fatalities, especially to unrestrained OOP occupants and children in relatively low speed crashes.

Due to this unintended safety consequence caused by air bags, decision-makers agreed that it was necessary to redesign air bags so that they would be safer for a wider passenger population. The longer-term solution was to develop more innovative technological solutions that can improve safety levels for all occupants during high-speed crashes, while, at the same time, reduce air bag-induced risks to OOP occupants, females and children. One of these new innovative technology solutions is advanced air bags, which can tailor the inflation force and deploy in a low-risk manner if warranted. For example, design features of advanced air bags will include multiple inflation force levels, improved folding patterns, and sensors to detect seat belt usage, occupant seat positions and occupant's weight. Thus, advanced air bags can determine the severity of potential impact and deploy with a lower force for OOP occupants, smaller-stature females and children.

While advanced air bags promised a long-term technology solution to irresponsible behavior (i.e., not using seat belts), regulatory changes were a short-term solution to fine tune the existing air bag technology in order for it to be safer for the general driving population. Thus, in March 1997, NHTSA made three interim regulatory changes that were extended until September 2000 to reduce air bag-induced risks. First, NHTSA amended FMVSS Section No. 208 to test vehicles with less aggressive sled tests as opposed to the previously used frontal rigid barrier test. Unlike the barrier test, no crashes occurred during sled tests. Instead, test vehicles were placed on sled-on-rails and accelerated backwards. Thus, the unbelted and belted dummies would move forward inside the vehicle in the same way that occupants would in a frontal crash. Air bags were then deployed at a pre-determined time and were kept consistent across manufacturers. This new performance standard of using sled tests allowed manufacturers to "de-power" or reduce air bag inflation forces by 20-35% so that they were less likely to injure occupants closer to the air bags. Starting in the 1998 model year, most vehicle models were sled-certified.

The second interim regulatory solution was that NHTSA permitted manufacturers to offer manual on-off switches in vehicles that did not have rear seats to accommodate rear-facing infant restraints. The manual on-off switches allowed drivers to deactivate air bags for their infants in the front passenger seats. In that way, air bag technology was not completely abandoned. Additionally, providing on-off switches in all vehicles meant reduced production costs for manufacturers since they did not have to have separate assembly lines during production. The third interim solution that was made by NHTSA allowed manual on-off switches to be *retroactively* fitted in vehicles. Around the same time that NHTSA amended the safety standards in FMVSS Standard No. 208, they also made a new regulation that required air bags to be installed in *all* vehicles as of 1997 (by the 1998 model year).

The sled test was an effective interim solution because manufacturers could de-power air bags to meet the performance requirements of the sled tests easily. On the other hand, developing new technologies, such as advanced air bags, required a longer time frame but was a better long-term solution. Thus, since manufacturers knew that the sled tests were a temporary solution, they could develop advanced air bags while meeting the interim amended standards of the sled tests.

Since then, air bag standards and regulations of the FMVSS have changed. Congress mandated that the introduction of advanced air bags should begin no later than September 2003, and be completed by September 2006. Starting from 2004, 35% of manufacturer's fleet in the U.S. was equipped with advanced air bag systems and that number rose to 100% by 2006. FMVSS Standard No. 208 also now specifically requires air bags to be designed so that they are more effective for a broader range of occupant weights, including the 5th-percentile adult female dummy, infant and child dummies, in addition to the 50th-percentile male dummy [118]. This change of standards that requires manufacturers to test air bags on a wider population reflected the interest and need in ensuring that the air bags technology will be safe beyond the average male adult. In addition, the new performance standards also phased out the interim sled tests and, again, phased in the more effective frontal rigid barrier crash tests at 25 mph for unbelted dummies and 30 mph for belted dummies. Also, manufacturers also have to meet more stringent injury performance standards. Thus, the current FMVSS Standard No. 208 for air bags provides a higher minimum level of safety standards.

4.1.6 Performance Standards and Innovation Implications

The increased minimum level of performance standards provided vehicle manufacturers with the incentive to develop advanced air bags. Note that the performance standards only specified that the unbelted dummies should survive at 25 mph and the belted dummies should survive at 30 mph. They did not draw out the specific design of any particular air bag technology (such as how air bags must be designed with weight sensors or occupant position sensors). Thus, manufacturers have the freedom to innovate and develop the advanced air bags in any way they desire, as long as the air bags could meet the stringent performance standards.

However, the setting of minimum safety standards is problematic in terms of whether innovation is encouraged or impeded. On one hand, the standards must be set high enough to encourage innovation; at the same time, the standards should not be set so high that it is not feasible for manufacturers to reach them.

4.1.7 Comparing Intelligent Warning Systems with Air Bags

Like air bags, intelligent driver warning systems represent another technology solution to improve safety levels on the roads. Data have shown that crashworthiness technologies have reached a stage of diminishing returns as the number of deaths from highway crashes has been stagnating at more than 40,000 each year in spite of these improving technologies. Thus, another major paradigm shift is needed, and technologies that can help prevent and avoid collisions, such as intelligent driver warning systems, are seen as the next solution.

4.1.7.1 Uncertain risks and benefits

When air bags were developed, there was significant uncertainty surrounding their benefits. Until air bags became widely installed in vehicles, their benefits were predicted primarily from engineering simulations and laboratory tests. Similarly, there are also uncertainties today regarding the safety benefits that intelligent warning systems can bring, and these uncertainties exist because there is not enough empirical evidence in support of these forecasted benefits. Just like for air bags, unintended consequences can appear after widespread diffusion and adoption of this emerging technology. Air bags, which were designed to protect occupants during collisions, were actually *causing* some deaths, and the extent of this problem was not foreseen during laboratory testing sessions before the air bags were actually marketed. Similarly, there are many concerns regarding the potential degradation of driver performance when using intelligent driver warning systems.

Thus, further human factors research into these issues is warranted before a definitive conclusion can be drawn. These negative effects of the warning systems are "known unknowns" (i.e., issues that are already forecasted to be potentials for serious effects if no solution is found) of the emerging technologies, which must be adequately addressed before the warning systems are deployed into vehicles. In addition, there are also the "unknown unknowns", which are unintended consequences that no one is able to forecast and predict. For air bags, the "unknown unknowns" were the air bags-induced deaths caused to children and female drivers that were not forecasted at all. Thus, due to these "unknowns", it is necessary that more human factors research is conducted on intelligent driver warning systems before they are released into the market.

4.1.7.2 Driver Population

Another similarity between intelligent driver warning systems and air bags is that certain populations of drivers may be protected at the expense of other populations. For example, in the case of air bags, the initial air bag design protected the typical male occupant at the expense of smaller-stature females and children. Similarly, for intelligent driver warning systems, certain high-risk drivers, such as novice and elderly drivers may face increased risks from the usage of these warning systems. Novice drivers have the least driving experience, and warning systems may increase their workload or distract them, thus degrading driving performance. Elderly drivers have naturally diminished cognitive and perceptual abilities that may limit the effectiveness of the warning systems. If safety standards for these intelligent driver warning systems are only specified and mandated for testing with the average driver, then unintended safety consequences may then arise for these risk-prone drivers. As shown from the development of air bags and the subsequent regulatory amendments made in 1997 to account for female drivers and child occupants, it is important that a larger driving population extending beyond the average is tested during the evaluation and certification tests of future warning systems before they are introduced into the market.

4.1.7.3 Minimum Standards

The case study on air bags technologies illustrates that manufacturers rarely innovate to *exceed* the "minimum" specified standards. Even though NHTSA mentioned that the performance standards of testing with the median male dummy was only a minimum requirement, and that it was up to the manufacturers to ensure that the air bags were safe for a wider population, that was not the case as the number of air bags-induced fatalities to women and children increased. This finding has implications for the setting of "minimum" safety standards for intelligent driver warning systems. If the regulatory agency should indeed set minimum standards for warning systems, then they must also ensure that the standards specify testing for a wider population range, especially for risk-prone drivers.

4.1.7.4 Market-Driven Innovation and Liability Concerns

Like air bags, the pace of warning system development and adoption may ultimately be market driven. For example, the introduction of air bags into the market began with the high-end market, which then diffused to the smaller-car market segment. Similarly for intelligent warning systems, ACC and LDWS have already appeared in the high-end consumer market and as interest in intelligent driver warning systems grows, it can be expected that these systems will soon be available in the smaller-car market segment. In addition, air bags were standard equipment in most vehicles by 1994, ahead of the regulatory schedule because of market forces. Advanced air bags also appeared in vehicles ahead of NHTSA's regulatory schedule of the phase-in of advanced air bags. Similarly, intelligent warning systems may very well become standard equipment in vehicles ahead of regulatory schedule.

Another similarity is that air bags were initially resisted by the industry primarily because of increased liability concerns for manufacturers. Similarly, for intelligent warning systems, liability concerns will also likely play a significant role and may potentially delay the introduction of intelligent warning systems into the market, especially Level 3 ADAS. In such cases, manufacturers may be reluctant to introduce the systems into the market, even if research proves that these systems are beneficial to drivers. This is because taking control away from drivers may result in increased liability concerns for manufacturers when accidents occur, especially when the Level 3 ADAS fail.

4.1.7.5 Differences between Air Bag Technologies and Driver Warning Systems

Despite all the parallels between intelligent driver warning systems and air bags, it must be noted that the one main difference between them is the critical component of driver-system interaction. For crashworthiness technologies such as air bags, little driver interaction is required in order for the devices to be effective. For example, drivers could not actively jeopardize the safety benefits of air bags by their actions or by their interactions with the air bags (unless they deliberately deactivated air bags using the on-off switches). On the other hand, for intelligent warning systems, the interaction between the driver and the warning system is critical for a safe outcome. Regardless of how "intelligent" these systems are, if drivers deliberately ignore the alarms, or if they are confused by the warnings and make inappropriate responses, then the warning systems will not be effective.

Another difference between air bags and intelligent driver warning systems may lie in the type of safety standards that exist. As illustrated in the air bags case, all the safety standards for air bags to date have been performance-based and none are prescription-based. For example, the safety standards amended by NHTSA in 2003 were performance standards (25 mph for unbelted male and female dummies and at 30mph for the same belted dummies). These safety standards were not prescription-based in that they did not mandate the use of a certain design such as a particular folding pattern, inflation force design, weight sensors, seat belts usage sensors, or occupant position sensors in order to ensure that the advanced air bags were able to protect the wide range of occupants and seating positions. Instead, only performance standards were set, and manufacturers were free to innovate and develop the advanced air bags technology to meet the minimum performance standards.

However, intelligent driver warning systems may need prescription-based standards in addition to performance-based standards because of the human-in-the-loop and interaction component of intelligent warning systems. Thus, design standards that actually specify the parameters of the warning systems may be warranted in order to mitigate some of the human factors issues that may arise. For example, design standards may specific that all alerts should be multi-modal. This specification may be warranted if future research shows that multi-modal alarms do indeed improve the performance of how drivers interact, accept, use and trust the systems.

The following sections will discuss what safety standards for intelligent driver warning systems currently exist and examine what type of standards should be applicable for intelligent driver warning systems, and what these standards should be.

4.2 Existing Safety Standards for Intelligent Warning Systems

As introduced briefly in Chapter 2, there are neither minimum performance or prescription-based standards, nor are there regulations that currently require the standardization of warning systems. Thus, manufacturers can introduce intelligent driver warning systems into their fleet of vehicles today in the United States without having to meet any minimum performance standards, unlike those required for advanced air bags today.

Nevertheless, there are human factors guidelines, which are design-based, created for display devices by both the ISO and the SAE. These guidelines are only recommendations for the design parameters of the intelligent warning systems and are non-binding for automotive and equipment developers of the systems [119, 120]. In the United States, these documents address user interface requirements for the Forward Collision Warning Systems and Adaptive Cruise Control Systems. In Europe, an example of a similar non-binding document is the "Statement of Principles on Human Machine Interface" from the European Commission [121].

Even though there are no formalized design standards today for intelligent warning systems, there is an international Working Group, WG14 (Vehicle/Roadway Warning and Control System) set up under ISO/TC204 with the aim of developing standardized intelligent driver assistance and warning systems across manufacturers. In particular, WG14 is tasked with investigating if current design guidelines suffice for vehicle-roadway warning and control systems, and if not, what new safety standards should exist. The scope of WG14 includes any driver assistance/warning systems that does the following: monitor the driving situation, warn of impending danger, avoid crashes, advise drivers of corrective actions and partially or fully automate driving tasks [122, 123]. Thus, WG14 is tasked with the standardization of driver assistance and warning systems that range from Level 1 to Level 3 ADAS. The existence of an international working group tasked with investigating what standards to set for intelligent driver warning systems further illustrates that these issues are important and more specifically, that it is important to incorporate human factors knowledge and principles into the design, deployment, and evaluations of these intelligent driver warning systems.

4.3 Policy Solutions

From the policy discussion in Chapter 2, it can be seen that there are a number of policy decisions that can be made with regard to the setting of safety standards. Policy solutions include varying how strictly safety standards are enforced by the regulatory agency. On one end of the spectrum, there are strict standards enforced by the regulatory agency. On the end of the spectrum, there are no enforced standards at all. However, the absence of any enforced standards does not literally translate to no standards, because more often than not, the industry self-regulates since liability concerns motivate manufacturers to ensure that their products are indeed safe. Thus, de facto consensus standards are developed, which are typically led by the leading manufacturers.

In addition, these standards can be either performance standards or design standards. Performance standards are typically technical standards that specify equipment performance (i.e., functional safety) or human performance (i.e., usage safety). Design standards typically specify principles and features appropriate to the technology. When design standards exist, there typically tends to be standardization of the warning systems across manufacturers. As previously discussed, automotive traditionally been performance-based but for intelligent driver warning systems, it is an open question as to whether there should be design standards too, and this is one of the questions this thesis address. Due to the large component of driver-system interaction and the human factors limitations of drivers, design standards may be warranted.

The best policy solution is the one that maximizes the benefits from the emerging technologies and utility to the stakeholders, while minimizing the costs (safety, health, environmental, economic) and unintended negative consequences. The benefits and costs of the various policy decisions will be discussed in the next section.

4.4 Tradeoffs Between Policy Solutions

The tradeoffs between the two types of policy solutions, having strict standards or not having any standards, are presented in this section. The tradeoffs are framed in terms of the overall welfare level of society, and are represented by the different welfare measures, including safety, time-to-market, innovation and economic costs.

Safety level is a tradeoff that can either be increased or decreased depending on which policy solution is chosen. Time-to-market represents the tradeoff of how soon the emerging technologies are introduced into the market, and how soon the public can enjoy the benefits of the technologies. Innovation represents the tradeoff of how superior the technologies that are present in the market are, and whether they are the state-of-the-art. Finally, economic costs represent the tradeoffs that tend to affect manufacturers in terms of financial outcomes. The category of economic costs will be explored in terms of liability concerns to manufacturers, which translate into significant economic costs. Economic costs that are incurred because of expensive certification, the research and development process, or benefits that are obtained based on sale of products are not considered. The tradeoffs of these four factors will now be explored, for the two extreme spectrums of the policy solutions: having no enforced standards at all and having strictly enforced standards. Table 8 summarizes the tradeoffs between these two policy solutions, which will be discussed in more detail in the next section.

Table 8: Summary of Tradeoffs between the Policy Solutions

Tradeoffs	**Policy Solution #1 – No enforced standards, i.e., de facto consensus standards set among manufacturers**		**Policy Solution #2 – Enforced standards by the regulatory agency**	
	Manufacturers	**Public**	**Manufacturers**	**Public**
Safety Levels	**OVERALL (-)**		**OVERALL (+)**	
	N/A	(-) / Costs: No minimum level of safety performance ensured.	N/A	(+) / Benefits: All systems perform with the same minimum level of safety.
Time-To-Market	**OVERALL (+)**		**OVERALL (-)**	
	(+) / Benefits: Faster time-to-market because no need to wait for the policy approval process.	(+) / Benefits: Get to benefit from the technologies sooner.	(-) / Costs: Policy cycle normally takes longer than the technology/innovation cycle. Thus, they may have delayed entry into the market.	(-) / Costs: Would not get to benefit from the technologies even if the technologies were ready and safe.
Innovation	**OVERALL (+)**		**OVERALL (+ or -)**	
	(+) / Benefits: Innovation likely because it is good to be the first to market.	(+) / Benefits: Would benefit from technologies resulting from competition.	(+) / Benefits: If standards are performance-based and if they are set high enough, they can encourage innovation.	(-) / Costs: Regulatory capture may occur which discourages innovation.
Economic Costs	**OVERALL (-)**		**OVERALL (+)**	
	(-) / Costs: Increased liability due to lack of clear, transparent rules and standards.	N/A	(+) / Benefits: Decreased liability because of presence of clear and transparent standards. Open market leads to increase in trade and capital flows.	N/A

4.4.1 Policy Solution 1: No Standards/De Facto Standards

The first policy solution is the option where the regulatory agency does not enforce any minimum performance or design standards. Thus, there are no enforced standards. Rather, the industry self-regulates, coming up with de facto standards. The tradeoffs are discussed in this section.

4.4.1.1 Safety: Overall Cost

The tradeoff of safety is an overall cost in this case. This is because there are no minimum safety standards that manufacturers have to meet and therefore, it is possible that some warning systems may not be as safe as compared to the case where standards are strictly enforced, since there is no agency regulating the warning systems. Some people may argue that even without the presence of enforced safety standards, the industry will still self-regulate, which is enough to ensure safety of the warning systems. While this may be true, I think that overall safety tends to increase with the presence of a regulatory agency providing oversight by enforcing the safety standards and deciding if the particular technologies get to market. Thus, without minimum safety standards, the public is more likely to be exposed to safety risks.

4.4.1.2 Time-to-Market: Overall Benefit

Time-to-market is an overall benefit because there is no policy process that may hinder the introduction of the intelligent driver warning systems into the market. In general, if there are no standards, when manufacturers feel that their systems are ready and safe for the market, they can introduce them into their vehicle fleets without having to go through tedious certification and testing process. This is also a benefit to the public since they will be given faster access to the emerging technologies.

4.4.1.3 Innovation: Overall Benefit

The tradeoff of innovation is an overall benefit because innovation tends to increase when there are no standards present, as opposed to the presence of any standards. This is because standards typically tend to impede innovation, unless the standards are *performance* standards, which are set high enough so that manufacturers have to innovate in order to reach that minimum level.

In the automotive industry, technological innovation is an especially significant determinant of economic growth and it is ideal to be a market leader through innovation [103, 104]. Innovation can include major radical shifts in technology or just incremental adaptation of existing technologies.

Thus, there are incentives for manufacturers to innovate and be the first to market, based on the "safety can sell" concept. Increased innovation will also benefit the public because, theoretically, if there is free competition, superior technologies will tend to survive and benefit society. Thus, if there are no enforced standards, then innovation will typically increase.

4.4.1.4 Economic Costs: Overall Cost

The absence of safety standards is an overall cost for manufacturers, in terms of litigation costs arising from liability. In the absence of government regulations that state clearly what the minimum safety performance and design standards are, the burden of proof lies with the vehicle manufacturers to ensure that their intelligent warning systems are safe. Thus, without the presence of clear and transparent minimum safety standards, it may not be clear to the manufacturers when they should stop the research and development process, and market the intelligent warning systems in their vehicle fleets.

In addition, without the presence of clear standards, should an accident occur arising implicating intelligent warning systems, then manufacturers will likely be held liable in the judicial system, especially product and tort liability law. For cases of product liability, if there is a defect in the product (i.e., the intelligent warning systems) such that safety is compromised, manufacturers would be liable to the plaintiff (the driving consumer). For cases of tort liability, if manufacturers were found to be negligent, they would be liable to the driving consumer as well. In the United States, in addition to compensatory damages (from product and tort liability), there may also be punitive damages, assessed by the court to punish the manufacturers. Because there are no pre-market safety standards for intelligent warning systems, the court has the power to rule on a case-by-case basis. Ruling on a case-by-case basis may not be optimal for manufacturers because the judicial system may not necessarily rule in their favor. Thus, due to this reason, there is a negative economic costs tradeoff for manufacturers if there are no safety standards.

4.4.2 Policy Solution 2: Strict Enforced Standards by Regulatory Agency

The second of the policy solution is the other alternative where the regulatory agency enforces minimum performance or design standards. In this case, the manufacturers must meet minimum safety standards in order to market their systems. The tradeoffs are discussed in this section.

4.4.2.1 Safety: Overall Benefit

In general, safety levels improve with the presence of safety standards, because safety is a large selling factor and high safety standards can assure that intelligent driver warning systems are safe. Thus, intelligent warning systems that are developed in the presence of enforced standards should generally have a higher safety rating than if there were no standards.

In addition, the presence of standards also communicates a message to the public that the warning systems are in the market because they have met a certain minimum safety requirement. Such standards balance the information asymmetry between manufacturers and the public, allowing the public to make informed choices based on how well the warning systems perform on the standards. Information asymmetry refers to situations during market transactions when one party has more information than the other party [124]. For example, in the case of intelligent driver warning systems, the automotive manufacturers have an information advantage because they develop the systems, while the public does not have much knowledge of the warning systems such as the safety performance of the systems. Thus, regulatory standards help to balance the information asymmetry by shifting more information to the public.

Thus, overall safety may potentially be increased if there are minimum standards, since consumers have a way of evaluating which warning systems are safer than others and can thus make more informed choices. Additionally, standards are a way of ensuring and controlling the quality of products in the market.

4.4.2.2 Time-to-Market: Overall Costs

The process of forming and harmonizing standards, especially on an international level, is a slow process. This is because time is needed in order to first set the standards, and then to test and certify that the warning systems meet the required minimum level of standards. For example, it can take 43 months to set standards in the ISO. This process is typically longer than technological development. Thus, standards always trail technological development. If the emerging technologies and products have to wait for the policies and standards to be shaped before they can be introduced into the markets, this poses an economic inefficiency to society, since the public cannot enjoy the potential benefits of the technologies. In addition, by the time the standards are set for a particular technology, the industry has probably moved beyond that initial development. Thus, having standards may sometimes lock-in inferior technologies.

4.4.2.3 Innovation: It Depends

The presence of safety standards could either help encourage innovation, or impede innovation, depending on the situation. On one hand, if the standards set are high enough so that manufacturers have to innovate in order to meet them, then innovation can be encouraged. In addition, performance-based standards (rather than prescription-based standards) can also encourage innovation since manufacturers will be motivated to meet, if not, exceed the minimum level of safety performance of their intelligent driver warning systems.

However, standards can also impede innovation. This can happen when the standards are not set high enough, primarily because of the phenomenon of regulatory capture. Regulatory capture is an economic theory of regulation, put forth by Stigler, which occurs when stakeholders who are supposed to be regulated (e.g., the automotive manufacturers) use the regulatory powers of the government to shape laws and regulations in a way that is beneficial to them [125]. For example, when the leading firms have developed a technologically superior product, they will benefit from a more stringent standard since they, and no one else, are able to meet it. Thus, these firms may try to convince the regulatory agency to use their technology as the standard and thus, they would have effectively "captured" the regulations to their advantage.

This phenomenon presents an inefficient economic outcome to society because regulatory capture by dominant firms results in the reduction of competition and the increase of barriers to market entry by other firms. Regulatory capture may also impede innovation, especially for the leading firms, who capture the standards so that they can comfortably meet them without developing superior products.

Thus, the tradeoffs of this policy solution of having standards are the innovation losses which can occur when the standards are "captured." The costs of innovation losses would then translate to welfare losses of society, who would have benefited from a more innovative and efficient product had the regulations not been "captured."

4.4.2.4 Economic Costs: Overall Benefit

In terms of economic costs, manufacturers will get to benefit from the presence of minimum standards for two major reasons: 1) The decrease in liability concerns because of the presence of transparent standards and 2) The increase in trade and capital flow arising from the formation of an interoperable and open market.

First, there are economic benefits to having enforced standards with transparent rules because manufacturers do not have to worry as much about whether their products adequately ensure safety. If there are clear standards that dictate whether the intelligent driver warning systems are certified safe or not, manufacturers would not be held completely liable for accidents arising from the use of the intelligent warning systems. For example, in the case of air bags safety standards, NHTSA's minimum standards dictated that air bags should be able to save the average male during a frontal barrier collision. However, when females and children were killed, manufacturers were not completely liable for the "failure" of the air bags, since their air bags were designed to perform to this minimum standard. In that case, it was NHTSA who had to make changes to the standards and to offer an improved solution. Hence, in terms of the extent of liability concerns, there are benefits to manufacturers in having clear minimum safety standards.

Second, having standards can also reduce barriers to trade in order to aid the opening of international automotive markets. The presence of standards and the harmonization of standards is crucial at a national and international level because they improve economies of scale and competition through the integration of infrastructure and markets. With respect to safety performance and design standards, if they are standardized across manufacturers and transcend national boundaries, then manufacturers will be able to make use of the interoperability of the markets and benefit especially from economies of scales and increasing rates of return. Thus, harmonized requirements that are standardized across manufacturers have economic benefits since the elimination of standards-related market barriers can help stimulate free trade and capital flow [103, 126].

4.5 Should There Be Safety Standards?

Driver warning systems were originally conceptualized to improve safety. However, despite the fact that intelligent driver warning systems such as the ACC and LDWS are already in the market, there are no regulatory standards to ensure that these systems are safe and that driving performance is not degraded when they are used. Moreover, as illustrated by the experiment conducted, unreliable warning systems can negatively and significantly affect driving performances. Thus, it seems necessary to have safety standards that ensure that intelligent driver warning systems in the market are reliable.

Because the interaction between these alarms and driver-machine interaction is still not well understood, improvement in automobile safety is not guaranteed by the presence of these emerging technologies. Thus, I argue that safety standards must be designed and set as soon as possible in order to ensure that future warning systems meet a minimum level of safety before they are introduced more widely into the market. In general, safety levels improve with the presence of safety standards, because safety is a large selling factor. Moreover, standards that are set high enough can provide incentives (especially performance standards) for manufactures to innovate, in order to meet and exceed a minimum performance requirement. Thus with safety standards, the intelligent warning systems that are developed should generally be of a higher performance level than if there were no standards. In addition, the presence of standards also communicates a message to the public that the warning systems in the market have been approved because they have met a certain minimum safety requirement.

Furthermore, in spite of the costs of having formalized standards, I argue that the benefits outweigh these costs, especially since the most salient benefit is increased safety. Costs that come with having safety standards include regulatory capture, the possible impediment of innovation, and the delayed introduction of the technologies into the market. Of these costs, one significant tradeoff is the increased time-to-market of the intelligent driver warning systems. Since there are no existing safety standards today, they would first have to be set, and this process can take a long time. Typically, the policy cycle is much longer than the technology/innovation cycle and thus, even though automotive manufacturers may be ready to introduce warning systems into the market, they have to wait and comply with the standards process, which can be tedious. Nevertheless, I argue that there is greater welfare gain to society of waiting for safe technologies to be developed, rather than to have the technologies in the market soon, but which may pose huge risks.

In addition, another cost associated with minimum standards is reduced open market competition, which arises because of regulatory capture, where leading firms may try to influence and capture the minimum standards to their advantage in order to prevent competition and increase the barrier to market entry by weaker firms. Unfortunately, this phenomenon of regulatory capture will always be present in any complex regulatory framework consisting of the various stakeholders such as the regulatory agency and industry. There have been debates with respect to the origins of standards in terms of whether standards were developed by the government in order to protect the public-interest goals (e.g., safety) or whether standards were actually initialized and requested by manufacturers as their way of securing government's assistance in order to transfer wealth to themselves, through regulatory capture [127]. The general consensus among academics has been that most standards were initiated by firms to secure assistance from the government in transferring wealth to themselves, in ways not attainable without government intervention or regulation at the expense of competitors and the public [125, 128].

Lastly, another cost is the impediment of innovation with the presence of safety standards. This occurs if the standards are not set high enough to, or are not designed to encourage innovation. For example, if standards are not set high enough, if manufacturers capture the standards to reflect the current-state-of-the-art, then there are no incentives for them to innovate. In addition, if the standards specify the use of certain technologies or certain designs for intelligent warning systems, then there is little incentive for manufacturers to innovate and try to develop superior products beyond the predetermined standards.

However, in spite of these costs arising from having standards, they can be minimized and addressed. If the standards are set high enough, then they will not inhibit innovation to a large degree, particularly if they are performance-based. However, it is true that regulatory capture may prevent these performance standards from being set too high, because manufacturers have an incentive to want the safety standards to be easily attainable. Thus, the risk of regulatory capture is a serious tradeoff in terms of leading to less open-market competition as well as less innovation. However, if the sharing of information is facilitated between the manufacturers, the regulatory agency, and the public, then regulatory capture may be minimized. This is because the regulatory agency will have the information needed in order to evaluate and to set the standards. In addition, the engagement of the public in the decision-making process can also reduce the extent of the capture phenomenon because the public's main concern will lie with the assurance of safety of intelligent driver warning systems.

Thus, because it is possible to minimize many of the costs and negative tradeoffs that come from having minimum standards, and because there are also long-term benefits in terms of improved safety, I argue that minimum safety standards are warranted. In addition, having safety standards can help to address latent problems and minimize unintended consequences. These latent and unintended risks that could arise from the widespread adoption of intelligent warning systems without any safety standards are irreversible (e.g., deaths that will be caused by poor designs are irreversible). Thus, I argue that overall safety in the longer run will be improved with the presence of safety standards. Since safety is of utmost importance, it should not be compromised at the expense of other benefits, especially economic, regulatory and judicial ones. Thus, it seems essential to err on the side of caution by enforcing safety standards in order to ensure that a minimum level of safety is maintained for intelligent driver warning systems.

4.6 What Safety Standards Should There Be?

As discussed in Chapter 2, safety standards can either be performance-based or prescription-based. Aspects of safety can be grouped into three main categories of functional safety, usage safety and traffic safety. In other words, for each of the safety aspects categories (especially for functional and usage safety), there can be safety standards set. These safety standards can further be divided into either performance-based or prescription-based standards.

Of the three, the first two safety aspects can be addressed using policy measures such as standards. The last aspect, traffic safety, incorporates large-scale interactions between drivers and the environment and is beyond the scope of this discussion. My recommendations for the types of standards to ensure functional and usage safety will be presented below.

4.6.1 Functional Safety: Performance Standards

Recall in Chapter 2 that functional safety of the intelligent driver warning systems is defined as the technical safety issues arising from both hardware and software design. The focus is on the technical reliability and robustness of the warning systems and their propensity towards malfunction. Thus, standards that address the functional system safety must ensure that at least on a minimum level, that the systems are robust, reliable, and fail-safe.

In terms of functional safety, the standards should be performance-based and set so as to ensure the development of reliable and robust systems. As seen from the previous experiment, warning systems with a reliability level of 25% induced poorer driving performance and produced more negative emotions in drivers, than those with a reliability level of 75%, which produced faster and more accurate responses. Since reliability of warning systems can be a critical determinant of the safety outcome of intelligent driver warning systems, it is imperative to set minimum performance standards to ensure that these systems perform to the specified requirement.

While I am not recommending these particular minimum levels of reliability, I do recommend that the performance standard for the assurance of functional safety include a *specified* minimum level of reliability of the intelligent warning systems that manufacturers have to meet. That way, manufacturers can innovate and use the least-cost method in order to design their systems in order to meet that minimum level of performance. In this way, innovation will be encouraged and not impeded, and at the same time, the public can also be assured of safe products in the markets.

Since multiple warning systems will be used together, it is imperative that performance standards specify performance requirements for ***multiple*** warning systems. This is crucial because certain interactions may arise when multiple warning systems are used together, but which do not arise when the individual warning systems are used in isolation. In addition, it is also important that the warning systems maintain robustness and reliability during multiple threat scenarios. Even though multiple threat scenarios (such as a lane departure causing a potential frontal as well as blind-spot collision at an intersection) may not be as common as single threat scenarios (such as lane departure or frontal collision), crucial issues may arise only during multiple threat scenarios, and these issues should be addressed as early as possible.

Finally, these performance standards should be harmonized internationally if possible, so as to ensure a consistent level of safety certification of intelligent warning systems beyond national boundaries. While I recommend performance standards to ensure functional safety, I do not recommend any prescription-based standards for functional safety. This is because specifying the actual design of the warning systems, such as the types of sensors to be used or the specific decision criterion for the warning systems, is unnecessary. As long as the final performance requirement is met, it is not crucial to standardize the design aspects of the warning systems that ensure functional safety. In addition, these design standards may also discourage innovation.

4.6.2 Usage Safety: Performance Standards and Design Guidelines

Recall in Chapter 2 that usage safety represents issues arising from the use of the warning systems. Thus, usage safety focuses on the *interaction* between drivers and the warning systems. Key issues involve inappropriate design leading to driver confusion, driver overload or underload, distraction from driving, lack of understanding leading to over or under-reliance and mistrust of the warning systems.

Thus, performance safety standards must ensure that driver performance is not degraded and that drivers comprehend the meaning of alarms and are able to respond with the appropriate action to mitigate the hazard. When developing these standards, it is important to have consistent testing scenarios and performance indicators across manufacturers so as to measure the driving performance. In addition, the indications must be objective and verifiable. For example, performance indicators could include reaction time, lane position, headway distance and accuracy of response. Testing scenarios should include all possible hazardous situations that can occur in reality and should also include multiple threat scenarios. Furthermore, other than objective driving performance as measured by these driving performance indicators, how the drivers respond to multiple threat scenarios should also be captured, including their affective state. This is important because as demonstrated in the experiment presented in Chapter 4, as well as in previous research, negative emotions can quickly lead to mistrust, lower acceptance and use of the warning systems, thus rendering them ineffective.

However, one main difficulty faced when developing usage safety standards is that critical scenarios and hazards are generally very rare (i.e., have low base rates). Thus, subjecting test drivers to multiple threats in a short period is unrealistic and does not mimic real driving conditions. Mimicking a low base probability of critical threats presents a tradeoff of increased costs stemming from longer testing periods and the need for a larger driver population. However, this tradeoff is necessary because the aim is to mimic real driving situations as closely as possible in order to support ecological validity. There have certainly been long-term large studies that were conducted, and such studies show that it is indeed important to conduct tests beyond the simulation in the laboratory [129]. In addition, unlike crashworthiness performance standards which are fairly mechanical since they involve dummies, testing and certifying the performance of the warning systems is only possible with real drivers. Thus, this is another complication and costs that will be incurred with the testing process.

However, despite these increased costs and tradeoffs to long-term research and testing, it is imperative that there must be performance-based standards to ensure usage safety of driver warning systems. This process will be slow initially but as more research is conducted and more data are obtained, the rate of returns will increase. Consequently, the level of safety of warning systems will be potentially raised as well.

In addition to performance standards for usage safety, there should also be prescription-based codes since the design may significantly affect how drivers interact with the warning systems. Nevertheless, I recommend that these codes should be recommended guidelines instead of standards, which the current status quo. In addition, I recommend that the many guidelines already present should be harmonized. As previously mentioned, there are many design guidelines which have been developed in countries including those in North America, Europe and Japan. Thus, while I recommend that design guidelines suffice (and design standards are not necessary), I strongly recommend that these guidelines be harmonized beyond national boundaries so as to share knowledge and to ensure that the latest human factors guidelines are available to manufacturers internationally.

Moreover, I argue that design guidelines suffice because it is still too early in the research and development process to determine optimal design parameters of intelligent warning systems. As such, it is not efficient for an inferior set of design parameters to be the standard. These technologies are still rapidly emerging and many human factors issues will likely arise from unanticipated driver-warning system interaction. Thus, if design standards are determined too early, they could lock-in an inferior set of design parameters. It is also not practical to wait for the research to develop and elucidate optimal design standards, since there will be the cost of delayed time-to-market.

The presence of performance standards for usage safety should ensure that future intelligent driver warning systems in the market are safe. However, the lack of design standards means that these warning systems will not be standardized across different manufacturers. Nevertheless, as long as usage safety is not compromised, then the lack of design standards should not be a crucial worry. As more manufacturers adopt these guidelines and more empirical data become available from the market, the optimal design parameters of warning systems can be developed, and these guidelines can then be potentially enforced as design standards. Examples of design guidelines can include whether to include a master alarm for integrated warning systems, how far apart temporally the multiple warning system alarms should occur, and the recommended modalities of the alarms. For example, if a master alert is indeed proven to be empirically better than multiple distinct alerts for the various warning systems, then the use of a master alert should be specified into prescription-based design standards later.

Nevertheless, even though the lack of design standards may mean that the warning systems in the market will likely not be standardized across manufacturers, I believe that customization of the warning systems is not a good option to offer drivers because design parameters, such as alarm presentation, is a safety critical feature. In addition, design parameters could also potentially have human factors implications. For instance, even though the experiment conducted did not show that a master alert had any affect on drivers' reactions as opposed to distinct individual alarms, one choice of alarm presentation may indeed be better than the other. In addition, the modality of presentation, such as auditory, visual, or haptic, may also affect how alarms are perceived. Thus, since design parameters are safety critical and may potentially have human factors implications, manufacturers should decide on the design parameters and not allow drivers the freedom of choice, since users may not always be right in wanting what is best for them [130]. In addition, from the manufacturers' perspective, it is also unlikely that they will allow the personalization of design parameters such as the choice of alarms because of the potential liability implications.

4.6.3 "Minimum" Standards

I also argue that it is not sufficient to have strictly "minimum" standards in the literal sense, because manufacturers will seldom exceed the standards, unless they have a vested interest such as economic profit to do so. Usage safety of intelligent driver warning systems should go beyond the strict minimum and include not only the average driver, but also include those of other higher-risk groups such as novice and elderly drivers. This standard must be enforced by the regulatory agency and should not just be a recommendation to manufacturers. I argue that this testing is necessary because the potential driver degradation that may occur with the use of intelligent driver warning systems is most likely with these risk-prone driving populations. In addition, the risks may be beyond what we are able to forecast today, and the extent of "unknown unknowns" and unintended consequences may be large. Thus, it is imperative to ensure that the warning systems work with all driver populations and to ensure that these emerging technologies will be safe for a wide driving population, even at the expense of the delayed market introduction of the warning systems.

4.6.4 Post-market Surveillance & Policy Flexibility

People will always find ways to maximize their personal benefits and utility derived from the use of the intelligent driver warning systems. In addition, people have an inbuilt target level of acceptable risk, which tends not to change. As a result, when new technologies such as intelligent driver warning systems are introduced into vehicles, people may drive faster or more recklessly since they want to maintain the same amount of target risk level, and are always seeking to increase their overall utility. This phenomenon is also known as behavioral adaptation or risk homeostasis. Since this phenomenon is unavoidable and people will always adapt their behavior to new technologies, it is not possible to forecast all risks and uncertainties associated with emerging technologies before they are actually in the market. As a result, while it is important to ensure that the intelligent driver warning systems are reasonably safe before they enter the market, it is also important to ensure that the technologies are introduced into the market without unnecessary delay so that the pubic can benefit from the use of these technologies.

As seen in the air bag example, it is impossible to forecast and detect all the risks from emerging technologies before they are actually used by a bigger population. Thus empirical data, informed by reasonable hypotheses, are necessary in order to learn how these warning systems will actually be used and accepted by drivers. Large-scale empirical data can only be obtained through post-market surveillance, which may be conducted by either manufacturers or a regulatory agency.

This can occur by keeping in contact with buyers, updating database of accidents caused/prevented by the warning systems, and conducting surveys, etc. to keep track of the potential effects of the warning systems. Post-market surveillance is even more crucial in the case of intelligent warning systems as compared to other automotive technologies because of the large component of driver-system interaction and the uncertainty of how drivers will respond to these systems.

In addition, flexibility should be designed into the policy-making process so that solutions can be easily changed and adapted as new information becomes available with empirical data from the post-market surveillance. Post-market surveillance and flexibility in adaptation are important because even though one policy solution may be optimal in a particular time period, that policy solution may not be suitable later.

It is often easier to maintain the status quo than to make a change. However, it is imperative that both the regulatory and engineering processes are adaptive such that technology lock-in and policy lock-in will be minimized, if not prevented. Lock-in tends to occur because there are increasing rates of return associated with maintaining the status quo of the incumbent technologies or policy decisions [87]. Increasing rates of return happens when there is a greater increase per unit output (e.g., economic gains) with a proportional increase per unit input (e.g., development and production costs). For example, as more factories are built to manufacture the particular product, it becomes increasingly cheaper to develop each marginal additional product. Increasing rates of returns will bias the decisions towards maintaining the current technology and policy decisions, rather than to making a radical change to adopt a new technology (even if that technology is superior) or to make changes to the policy decisions [131]. Thus, both policy and technology feedback are essential to foster learning and anticipation of change in the policy decisions. This feedback can be obtained via close-monitoring and post-market surveillance.

4.6.5 Importance of Sharing Information

Also important is the exchange of information between the main stakeholders: the regulatory agency whose job is to ensure minimum safety standards are met, the automotive manufacturers whose interests lie with profit maximization, and the public whose interest lie in increasing their overall utility. However, if regulatory agents do not have the information that the manufacturers have about their warning systems such as the state-of-the-art of the emerging technologies, then regulatory capture may occur, as manufacturers try to influence and shape the regulations and standards to their advantage. Unfortunately, regulatory capture is a phenomenon that is going to be present in any complex regulatory framework. For example, in the case of setting minimum safety standards for intelligent driver warning systems, there are international organizations set up to look into these issues such as the Society of Automotive Engineers (SAE). However, these organizations are mainly composed of the manufacturers themselves, who are likely to influence the final outcome of what safety standards are set. Thus, to reduce regulatory capture, it is important to facilitate the exchange and sharing of information between the and the regulatory agency so that the regulatory agency will have the information to evaluate and set the standards. In addition, the engagement of the public in the decision-making process can also reduce the extent of the capture phenomenon because the public is more concerned about the assurance of safety of the intelligent driver warning systems than profit maximization.

4.7 Conclusions

Until now, the development of intelligent driver warning systems has been strongly technology driven, and minimum safety standards are non-existent today that ensure that these systems are safe. With the absence of any enforced performance or design safety standards, it is possible that intelligent warning systems could actually degrade driving performance in some situations. Even though there may be certain benefits that come with not having any enforced standards, there are more justifications to having a minimum level of safety standard for intelligent warning systems before they enter the market. The main and most salient benefit from having enforced minimum standards is that safety levels will be ensured and increased in the long run. Other benefits of having standards include clear and transparent rules so that manufacturers know exactly what levels of safety are required, and innovate accordingly, as well as possibly increased levels of innovation if standards are set high enough.

In terms of functional safety, there should be performance-based standards to ensure that the warning systems will not fail. These performance standards should be standardized across manufacturers and if possible, harmonized internationally, so as to ensure a consistent level of safety certification. In terms of usage safety, there should be performance standards as well. Indicators that measure driving performance and usage safety include drivers' reaction time to critical hazards, lane position, headway distance and accuracy of response. It is also imperative to develop standardized driving scenarios in evaluating driving performance and thus, usage safety. Furthermore, how drivers respond to critical hazards should also be captured, including their affective state. Like the standards for functional safety, performance standards for usage safety must also include multiple threat scenarios to investigate how drivers will respond to multiple intelligent warning systems.

Since the design parameters of the warning systems may actually be significant factors that affect driving performance, there should also be design guidelines in addition to performance standards. However, since it is too early in the development process to formalize strict design standards, I recommend that the current status quo of having human factors guidelines suffice. However, the various design guidelines developed from the various organizations including those in North America, Europe and Japan should be harmonized beyond national boundaries. That way, manufacturers across the world can be consistent in the design of the intelligent driver warning systems.

The presence of performance standards for both usage and functional safety should ensure that future intelligent driver warning systems in the market are safe. The lack of design standards means that these warning systems will not be standardized across different manufacturers. Nevertheless, as long as usage safety is not compromised, then the lack of design standards should not be a crucial concern. As more empirical data and research become available on the operational use of the warning systems, then these design guidelines can be adapted as design standards.

Moreover, since the industry cannot be relied on to go beyond the "minimum" standards, it is imperative that the "minimum" safety standards of the warning systems include driver performance of different driving populations, extending especially beyond the median driver to include risk-prone populations. This is especially important since these are the populations at the most risk from the introduction of the intelligent driver warning systems into vehicles.

Finally, since it is impossible to detect all risks before the warning systems are fully introduced into the market, it is important to follow-up with rigorous post-market surveillance of how the warning systems actually perform empirically. The regulatory framework consisting of the decision-makers and major stakeholders should be flexible enough to allow for adaptation and change of policy decisions, safety standards, and regulations to ensure that the technologies available in the market are the best possible. This is important because a flexible regulatory system can minimize, if not prevent, technology lock-in to inferior technologies and regulatory lock-in to inferior policies. Finally, to ensure that the intelligent driver warning systems being developed will be superior and safe, it is important for information to be shared and exchanged between the various stakeholders.

Chapter 5

Conclusions

This thesis was concerned with examining multiple intelligent driver warning systems that will soon be installed in a significant number of vehicles. Specifically, driving performance implications in using a master alert as opposed to multiple distinct alerts from multiple warning systems were examined. Additionally, this thesis was concerned with exploring whether there should be minimum safety standards for intelligent driver warning systems, and if so, what these safety standards should incorporate, as well as the potential implications of setting safety standards.

5.1 Driver Experiment

A 2x4x2 laboratory simulation experiment with a mixed factorial design was conducted to determine if a master alarm would impact driving performance differently in the presence of multiple intelligent warning systems, as opposed to distinct individual alarms. The three factors designed in the experiment were alarm alerting scheme (master vs. multiple alerts), driver warning systems (front and rear collision warnings, left and right lane departures), and reliability (high and low reliability levels). Reliability was also chosen to be one of the factors tested since no warning systems will be perfectly reliable. A secondary distraction task was included to draw drivers' attention away from the roadway and to emulate in-car telematic distraction. The auditory modality was chosen as the channel of alarm presentation because of its omni-presence and its ability to direct attention of drivers, regardless of initial attention focus.

The experiment showed that the master alert did not make a difference in drivers' performance for both reaction time and accuracy of response when compared to multiple distinct alarms. On the other hand, both reliability and the specific driver warning systems were significant factors that affected driving performance. Expectedly, reaction times were very different for the four different types of hazards. For example, reaction time was expected to be shorter for responses to mitigate frontal collisions than those for rear collisions because drivers generally can be expected to focus more on the frontal visual scene as opposed to the rear visual scene. The factor of reliability was also significant in affecting both the reaction times and the accuracy of responses of the drivers. When participants drove with more reliable warning systems, their reaction times were shorter and more accurate. Warning systems with low reliability also negatively influenced drivers' affective state, such as creating stress and anxiety. This finding highlights the need to develop reliable and robust warning systems that have low incidences of false, nuisance and missing alarms. Another important result from the study was that even though driving performance was not affected by the use of either a master alarm or distinct alarms, participants' responses in the post-experimental survey indicated they generally preferred distinct alarms, instead of a generic master alert.

There are three design implications of the results from this experiment. First, designing systems that are reliable is of paramount importance. In other words, if warning systems are not reliable (i.e., there are many false, nuisance, and missing alarms), then drivers are potentially better off without them. Unreliable systems tend to increase stress and anxiety levels of drivers, leading to distrust of and a lowered confidence in the warning systems, which subsequently lowers acceptance of the driver warning and assistance systems. Previous studies have also demonstrated this effect where unreliable systems degraded driver performance as well as negatively affected drivers' emotions. Thus, the reliability of these intelligent driver warning systems is one of the most crucial determinants of driving performance.

A second implication of the results is that the use of a master alert did not make a difference in either improving or degrading driving performance. However, this result must be evaluated in light of the circumstances in which the experiment was conducted: only auditory alarms were tested, a limited number of driver warning systems were tested, and there were a high number of critical hazards that occurred in the testing period. Results may be different if multi-modal alarms are used and if more warning systems are tested to reflect the proliferation of warning systems. Additional research into the implications of using a master alarm for multiple warning systems should be done before a definitive conclusion of whether a master alarm helps to increase or decrease driver performance.

Another implication from the post-experiment survey administered was that participants generally thought that they would do better with distinct alarms than a master alert. The implication of this finding is that if further research also shows that driving performance is indeed unaffected by the alarm alerting scheme, then perhaps manufacturers can cater to the preferences of drivers by allowing drivers to choose and personalize the alarms from the warning systems in their vehicles.

5.2 Importance of Setting Minimum Safety Standards

Driver warning systems were originally conceptualized to improve safety. However, despite the fact that intelligent driver warning systems such as the ACC and LDWS are already in the market, there are no regulatory standards to ensure that these systems are safe and that driving performances are not degraded when they are used. Because the interaction between these alarms and driver-machine interaction is still not well understood, and improvement in automobile safety is not guaranteed by the presence of these emerging technologies, I argue that safety standards must be designed and set as soon as possible in order to ensure that future warning systems meet a minimum level of required safety. These safety standards should be met before the intelligent warning systems are introduced more widely into the market.

In general, safety levels improve with the presence of safety standards because safety is a large selling factor and performance standards that are set high enough can provide incentives for manufactures to innovate. Thus, with safety standards, intelligent warning systems that are developed should generally be of a higher performance level than if there were no standards. In addition, the presence of standards also communicates a message to the public that the warning systems in the market have been approved because they have met a certain minimum safety requirement.

Nevertheless, there are tradeoffs that come with the presence of minimum standards. One significant tradeoff is the increased time-to-market created by the presence of standards. Since there are no existing safety standards today, they would first have to be set and this process can take a long time. Typically, the policy cycle is much longer than the technology/innovation cycle and thus, even though automotive manufacturers are ready to introduce warning systems into the market, they would need to wait and comply with the standards process, which can be tedious. Another cost associated with minimum standards is in terms of reduced open market competition which can arise because of regulatory capture. Lastly, innovation may also be impeded with the presence of safety standards, especially if the standards are not set high enough to encourage innovation.

In order to minimize the phenomenon of regulatory capture, it is important to facilitate the exchange and sharing of information between manufacturers and the regulatory agency so that the regulatory agency will have the information needed to evaluate and set the standards. The engagement of the public in the decision-making process can also reduce the extent of the capture phenomenon because the public's main concern will lie with the assurance of safety of the intelligent driver warning systems. Thus, the exchange of information is crucial to prevent regulatory capture from negatively impacting safety standards.

Nevertheless, in spite of the potential tradeoffs that may occur with the presence of safety standards, the benefits of improvements in safety that come from having minimum standards are long-term and are thus warranted. In addition, the risks from the widespread adoption of intelligent warning systems without any safety standards are often irreversible (e.g., deaths that will be caused by poor design are irreversible). Furthermore, safety has an intrinsic value to consumers and thus, it should not be compromised. Thus, it is essential to enforce safety standards in order to ensure that a minimum level of safety is maintained for intelligent driver warning systems.

5.3 Recommendations for Minimum Safety Standards

In terms of what minimum standards should be set, I recommend that safety standards be set for both functional and usage safety of intelligent warning systems. In terms of functional safety, standards should be performance-based and must be set to ensure the development of robust and reliable systems. As seen from the experiment conducted, warning systems with a reliability level of 25% induced poor performance, as compared to those with a reliability level of 75%. While I am not recommending these particular minimum levels of reliability, I do recommend that the performance standard for the assurance of functional safety include a *specified* minimum level of reliability of the intelligent warning systems that manufacturers have to meet. That way, manufacturers can innovate and use the best available technologies in order to meet and exceed the performance standards. However, for functional safety, there should not be any design standards because such standards would discourage innovation.

In terms of usage safety, standards must also be performance-based to ensure that driver performance is not degraded by the warning systems. However, at this point in time, it is too early to dictate specific design standards, so I recommend that the current design guideline status quo is sufficient. However, there are many human factors design guidelines which have been developed in

North America, Europe and Japan. Thus, I also strongly recommend that these guidelines be harmonized beyond the national boundaries so as to share knowledge and to ensure that the latest human factors guidelines are available to manufacturers internationally. In addition, not having any design standards for the systems will also allow a quicker time-to-market of the warning systems. If design standards are set early in the process, more human factors research will have to be done and this may unnecessarily delay the introduction of otherwise safe warning systems into the market.

Thus, the presence of performance standards for both usage and functional safety should ensure that future intelligent driver warning systems in the market are safe. However, the lack of design standards would mean that these warning systems would not be standardized across different manufacturers. Nevertheless, as long as usage safety is not compromised (by the presence of performance standards), then the lack of design standards should not be a crucial concern. However, I argue that in the long run, there should be design standards, especially when it becomes clear that a particular design configuration is superior. I also recommend that warning systems be standardized across manufacturers in the long run. For example, if a master alert is indeed proven to be empirically better than multiple distinct alerts for the various warning systems, then the use of a master alert should be specified into the design standards.

One crucial point to note is that when setting these "minimum" safety standards, especially for performance-based standards, it is imperative that the standards account for a wide driving population, extending beyond the median driver to include risk-prone populations like novice and elderly drivers. This standard must be enforced and should not just be a guideline to manufacturers. As seen with the development of air bag technologies, performance standards initially only included the median male. However, as air bag-induced fatalities began to rise for females and children, NHTSA amended the standards to include performance tests for female and children dummies as well. Likewise, for intelligent warning systems, it is absolutely imperative that the performance standards are not just tested with the average driver, but also for peripheral driving populations. In addition, we can learn from the air bag example and ensure that minimum standards include a wider driver population in order to address these forecasted risks before wider market proliferation.

5.4 Recommendations for other Policy Measures

While it is important to set safety standards to certify that warning systems are safe before release into the market, it is also important not to delay the introduction of such potentially beneficial technologies. This is because it is impossible to detect all risks from emerging intelligent driver warning systems until they are fully introduced into the market. Thus, it is important to introduce the systems into the market as soon as possible so that the public can benefit from the technologies. At the same time, it is imperative that manufacturers and regulatory agencies conduct rigorous post-market surveillance of how these warning systems perform empirically, as a follow-up to this initial introduction. This post-market surveillance is even more crucial in the case for intelligent warning systems because of the large component of driver-system interaction and the uncertainty of how drivers will respond to the systems.

Post-market surveillance may shed light on unintended safety consequences as more empirical data is collected over time. When there is an indication of such risks, the regulatory system should be flexible enough to allow for adaptation and change of the policy decisions and safety standards in order to ensure that new risks are addressed. If this flexibility and adaptation is incorporated into the regulatory framework, then both technological lock-in to inferior technologies as well as regulatory lock-in to inferior policies can be minimized, if not avoided.

Lastly, it is also important that information is shared between the major stakeholders consisting of the regulatory agency, the industry (the manufacturers) and the public. This exchange of information is important to ensure that the regulatory agency will have sufficient knowledge and information about the current state-of-the-art of the intelligent warning systems in order to minimize the phenomenon of regulatory capture and to be able to set minimum safety standards that will encourage manufacturers to innovate. In addition, public opinion is also very important and should be heard in the decision-making process. This is especially true for intelligent warning systems, which have a large component of driver-machine interaction. Thus, choices made regarding the design and development of intelligent warning systems are also social ones that public should have a say in. The role of the regulatory agency is to ensure that emerging technologies such as intelligent driver warning systems in the market are safe, but their role is not to ensure that the technologies available are the most superior technologies. However, if more stakeholders such as the public are included in the decision-making process of deciding on both the direction and development of these technologies as well as on the minimum levels of safety desired, then it can be ensured that the technologies in the market will be superior to those that would exist if there was no public scrutiny. This is because if consumers can input their wants and needs into the decision-making and design process, then they can help shape the development and innovation of the technologies to be as close to the ones desired as possible. Thus, if this exchange of information is facilitated between the major stakeholders, then economically efficient outcomes of having both *superior* and *safe* intelligent driver warning technologies will be achieved.

Appendix A

Tables A1 and A2 shows the list of vehicles equipped with systems that support lateral control of the vehicle, namely, Lane Departure Warning Systems (LDWS) and systems that support longitudinal control, namely, Adaptive Cruise Control (ACC) Systems available in the United States light vehicle market for the 2005/2006 model year. The Tables A1 and A2 categorize these ADAS (i.e., ACC and LDWS) according to the vehicle manufacturer (i.e., Mercedes), model line (i.e., E-class), and model trim level (i.e., E500).

List of Vehicles with ACC

Table A1: List of Vehicles equipped with ACC (2005/2006 models). [31]

Make	Model	Trim Level	Year
Audi	A8	LW12 Quattro, L42 Quattro, 4.2 Quattro	2005
BMW	3 Series	325i, 330i	2006
	5 Series	525i & 525xi, 530i, 530xi & 530xi Sportswagon	
		545i	2005
	6 Series	645Ci	
	7 Series	750i, 750Li, 760i, 760Li	2006
Cadillac	STS	V8	2005
	XLR	-	
Infiniti	FX	FX35, FX45	2005
	M	M35, M35xAWD, M45, M35 Sport, M45 Sport	2006
	Q	Q45	2005
	QX	QX56	
Jaguar	S-Type	3.0, 4.2, 4.2 VDP Edition, S-Type R	2005
	XJ-Series	Super V8, Vanden Plas, XJ8, XJ8L, XJR	2005
	XK-Series	XK8, XKR	2006
Lexus	GS	300, 430	2006
	LS430	-	2005
	RX	330	2005
Maybach	--	57, 62	2005
Mercedes-Benz	CL-Class	CL500, CL55, CL600, Cl65	2005
	CLS-Class	CLS500, CLS55	2006
	E-Class	E55	2005
	S-Class	S350, S430, S500, S55, S65, S600	2006
	SL-Class	Sl500, SL55, SL600, SL65	2005
	SLR	-	2005
Toyota	Avalon	Limited	2005
	Sienna	XLE Limited	2005

List of Vehicles with LDWS

Table A2: List of Vehicles equipped with LDWS (2005/2006 models)[31].

Make	Model	Trim Level	Year
Infiniti	FX	FX35, FX45	2005
	M	M35, M35xAWD, M45, M35 Sport, M45 Sport	2006

Appendix B

FCW Triggering Events

1. Oncoming vehicle on highway that overtakes another car, resulting in a head-on impending collision. The head-on oncoming car does not swerve back into its own lane.

Figure 1: At Top of Hill, an Oncoming Car Appears

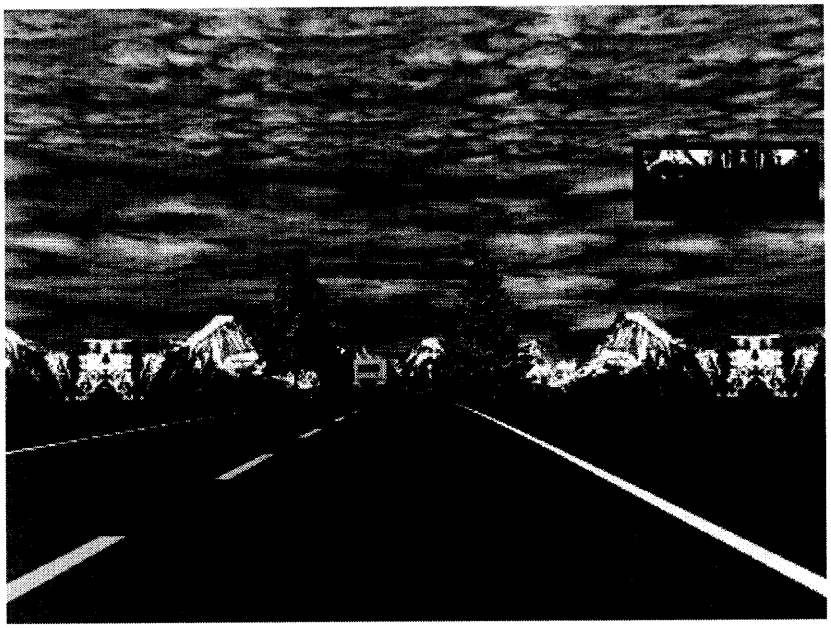


Figure 2: Oncoming Vehicle Imminent Collision

2. Lead moving vehicle on highway that brakes suddenly.

Figure 3: Suddenly Braking Car

3. Stationary parked vehicle that pulls out from the side onto the driver's path.

Figure 4: Stationary Car Pulling into Driver's Path

4. Stationary parked vehicle that backs out from a garage onto the driver's path, and then backs into the garage again.

Figure 5: Rows of Parked Cars in Housing Estate

Figure 6: Car Backing Out & In of Garage

FVFA Triggering Events

There is basically one type of FVFA triggering event, which was a vehicle that quickly approaches the driver from the rear, with a closing velocity of 50 feet/second more than the speed of the driver. There were two ways by which the other vehicle could retreat at the last moment without crashing into the subject driver:

1. The moving rear vehicle surges up to the driver, and then backs off at the last moment when the 2 vehicles are within 2 feet of each other.

Figure 7: Rear Car Approaches Driver As Driver Reaches End Of Downhill

Figure 8: Rear Car Gets Closer to Driver

Figure 9: Rear Car Then Backs Away

2. The moving rear vehicle surges up to the driver, and then overtakes on the driver's left when the 2 vehicles are within 2 feet of each other.

Figure 10: Rear Car That Overtakes Driver on Left

Figure 11: Rear Car Speeds off after Overtaking

LDW Triggering Events

The unexpected "wind gust" will force a gradual heading change and subsequent lane change to the left or right of the participant's vehicle. Participants will then experience a heading change of their vehicle and will have to correct the departure by steering back into the lane of travel.

Appendix C

Testing Scenario A (TP:FP = 3:1)

Table C1: Random Order of Appearance of the Critical Events (TP & FP) in Scenario A

Distance (ft)	TP/FP	Left LDW	Right LDW	FCW	FVFA
2900	TP	TRUE 1			
4340-4500-5300	TP				TRUE 1
6350	TP	TRUE 2			
7900	TP		TRUE 1		
11300	FP		FALSE 1		
12380	TP		TRUE 2		
13900- 14200	TP			TRUE 1	
15300- 15880	TP				TRUE 2
17500 - 18300	TP				TRUE 3
19600	TP	TRUE 3			
22000	TP				TRUE 4
22500	TP			TRUE 2	
24300	TP		TRUE 3		
25600	FP	FALSE 1			
26380	TP		TRUE 4		
27800	FP		FALSE 2		
29300	TP	TRUE 4			
32000- 35000	TP				TRUE 5
33800	TP		TRUE 5		
36500	TP			TRUE 3	
37500	TP			TRUE 4	
38800	FP			FALSE 1	
39000	FP	FALSE 2			
40200	TP	TRUE 5			
41590 - 40650	TP			TRUE 5	
42500	FP				FALSE 1
44000	TP		TRUE 6		
45000	FP			FALSE 2	
46380	FP				FALSE 2
47800	TP			TRUE 6	
48500	TP				TRUE 6

Testing Scenario B (TP:FP = 1:3)

Table C2: Random Order of Appearance of the Critical Events (TP & FP) in Scenario B

Distance (ft)	TP/FP	Left LDW	Right LDW	FCWS	RCWS
2500	FP	FALSE 1			
3800	FP		FALSE 1		
6500	FP				FALSE 1
7900	TP	TRUE 1			
9900	FP		FALSE 2		
11300	FP		TRUE 1		
12380	FP	FALSE 2			
13150	FP			FALSE 1	
14148	FP				FALSE 2
15500- 16000	TP				TRUE 1
17000	FP	FALSE 3			
19200	TP		FALSE 3		
20900	TP			FALSE 2	
21900- 23000	TP				TRUE 2
24300	TP			FALSE 3	
26200	TP				FALSE 3
27000	FP			FALSE 4	
27800	FP		FALSE 4		
29000	TP			TRUE 1	
31200					FALSE 4
33200	FP			FALSE 5	
34000	FP	FALSE 4			
35200	TP				FALSE 5
36650	TP			TRUE 2	
37600	TP	TRUE 2			
38700	FP	FALSE 5			
39700	TP		FALSE 5		
41500	FP				FALSE 6
46000	FP			FALSE 6	
47300	TP		TRUE 2		
48500	FP	FALSE 6			

Appendix D

Participants' Informed Consent Form

CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

Multiple Warnings and Driver Situation Awareness

You are asked to participate in a research study conducted by Angela Ho and Dr. Mary Cummings from the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (M.I.T.). You were selected as a possible participant in this study because you are between the ages of 18 and 55 and hold a valid drivers license. You should read the information below, and ask questions about anything you do not understand before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- **PURPOSE OF THE STUDY**

The study is designed to evaluate how different alarms in Collision Avoidance Systems affect human performance.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to:

(1) First fill out pre-test questionnaires on your driving tendencies and experiences.
(2) Sit in and drive the vehicle simulator "Miss Daisy" through a virtual environment as part of acclimatizing yourself with the simulator environment for up to 15 minutes.
(3) Various different experimental runs will follow during the next 45 minutes. You will be asked to drive through a series of simulated scenarios which will test your ability to discriminate between different types of aural alarms (forward collision & real collision). Driving data will be collected based on different responses to alarms triggered by the collision avoidance systems.
(4) Lastly, fill out a post-test questionnaire on your simulator experience.

- **POTENTIAL RISKS AND DISCOMFORTS**

There are no major risks anticipated from participation in this study. There is a slight chance of experiencing simulator sickness a similar experience to motion sickness. Please inform the experimentor at the first sign of any discomfort. Should you wish to stop or delay the experiment, you are free to do so at any time.

- **POTENTIAL BENEFITS**

You will have a chance to participate in research that will increase knowledge of human behavior and response to different alarms in Collision Avoidances Warning Systems. In the future this data may contribute to affecting designs of these systems, and be used to improve vehicle and roadway safety.

- **PAYMENT FOR PARTICIPATION**

Participation in this study is strictly on a volunteer basis and no compensation other than the gratitude of the investigators and possibly free snacks and drinks will be provided.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. You will be assigned a subject number that will be used on all related documents to include databases, summaries of results, etc. Only one master list of subject names and numbers will exist that will remain only in the custody of Professor Cummings.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact Angela Ho (617-452-4785) or Dr. Mary Cummings (617-252-1512).

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253-2822.

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Subject

____
Name of Legal Representative (if applicable)

____________________________________ ____________
Signature of Subject or Legal Representative Date

SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

____________________________________ ____________
Signature of Investigator Date

Appendix E

Participants filled out a pre-experiment survey on a desktop computer, and their answers were electronically stored. The survey questions are reproduced below:

Pre-experiment Survey

Hello and thank you for participating in the Driving Study conducted by Professor Mary L Cummings and Angela Ho.

Please fill out the following Pre-Simulation Questionnaire. We look forward to your participation at E40-292

If you have any questions, please direct them to AngelaHo@mit.edu. Thank you.

Please fill in blanks or circle the one best response unless otherwise noted.

Your answers to these questions will be held confidential.

1. What is your subject ID (Part1)?*
   Please ask the research assistant for your Subject ID.
2. What is your subject ID (Part1)?*
   Please ask the research assistant for your Subject ID.
3. How old are you? ____________
4. What is your gender? male female
5. What is your occupation? If student, list your major.

   ____
6. How many years have you had a valid driving license (answer in years)?
7. On which side of the road are you used to driving? If your'e comfortable driving on both sides, select "both." For example, in the US and Canada, select "right" side of the rod. In united Kingdom and Commonwealth countries, select "left" side of the road.
   _Right _Left _Both

8. Do you have a:

   a. US License
   b. Canada License
   c. If International, which Country? ________________

9. When was the last time you drove? Choose your timescale and write it in next to your answer. For example "1 month ago" or "2 days ago" or "5 years ago" ________
10. In the **last year**, how often did you drive? Each 'time' is defined by each trip you make on a car.

   a. 5 days a week or more
   b. 3 - 4 days a week
   c. a few times each month
   d. Less than 10 times a year
   e. Less than 5 times a year

11. In the **last year**, on a typical weekday, what is the **total distance** and **time** you drove?

Please answer considering a day which is typical for you, or approximate the average time you would spend driving on a weekday. _____ miles ________ hours

12. On a scale of 1-10, how would you characterize your typical driving behavior?
1 being least aggressive, and 5 being most aggressive.
1 2 3 4 5

13. When you drive, do you have difficulty keeping to your own lane? No
Yes. Please further explain when does that happen, and why?

____

____

____

14. Do you feel drowsy right now? Yes no

15. In which, if any, of the following do you usually get motion sick? (check all that apply)

   - ○ Playing Video Games
   - ○ A train facing backwards
   - ○ A train facing forwards
   - ○ A bus
   - ○ The driver seat of a car
   - ○ The passenger seat of a car
   - ○ The back seat of a car
   - ○ An airplane
   - ○ Moving boat
   - ○ Other please specify ________________
   - ○ None of the above

16. Do you take motion sickness medication, such as Dramamine, before traveling in? (circle all that apply)
    - A train
    - A bus
    - Car
    - An airplane
    - A boat
17. How often do you play video games (PS, Xbox, Computer, Arcade, etc)
    Never. No time.
    I play it a few times a year
    I play it a few times a month
    I play it a few times a week
    I play it more than a few times a week, but I can control how much I play.
    I'm addicted. I have withdrawal symptoms if I don't play. Help!

Thank you for completing the survey! Don't forget to go to E40-292 on your scheduled day for the experiment. Thanks!

Appendix F

Transcripts of Voice Instructions

All participants heard pre-recorded voice instructions, spoken by a female American, so as to reduce any variability between participants with respect to the instructions heard. The following shows the transcripts of these instructions.

Introductions

01.SILENT_PHONE.mp3

Please remember to turn your cellular phone to the silent mode.

01.INTRODUCTION.mp3

Hello and welcome to the MIT driving lab.

Please make yourself comfortable, and adjust your seat as you would if you were driving a real car.

This car functions as an automatic so you will not need to shift or use the clutch.

Look directly ahead and you will see a large screen, which will soon display the driving course.

On the right side of the screen, a rearview mirror is projected.

The simulator also has a working speedometer and functional turning signals.

During the simulated drive over the next 40 minutes, you are going to drive through different types of environments.

You will be hearing warning alarms sound during your drive.

This may mean that you are encountering a potential frontal collision, rear collision, or that you are drifting out of your own lane.

In such cases, if you do not take a corrective action, a crash is imminent.

However at other times, the warning alarms may just be false alarms. This means that there are no potential collisions taking place, and the warning alarms are false alerts.

You will now hear some examples of the warning alarms.

Introduction – Master Alarm

- ***Plays either master alarm or the distinct alarms. Alarm alerting scheme is a Between-Subject factor, so half of the subjects under the Master alarm alerting scheme heard the following instructions while the other half heard another set of instructions:***

02A1.MasterAlarm.mp3

If you are about to have a frontal collision, a rear collision, or

If you drift out of your lane onto either the left or ride side of the road, you will hear this alarm sound:

- ***Plays master alarm***

02A2.AfterMasterAlarm.mp3

You have heard the ***same*** alarm sound.

When you hear such an alarm, it may mean that you are experiencing a variety of events.

Firstly, you may be about to have a frontal collision. To avoid a crash, you can either apply the brakes or swerve onto the sidewalk

You may also be about to have a rear collision. To avoid being rear-ended, you can either Speed Up or swerve onto the sidewalk.

In addition, you may also be drifting out of your lane.

When this happens, you should maintain control of the steering wheel and go back into your lane.

Introduction – Multiple Distinct Alarms

- ***The other half of the participants under the multiple alarm alerting scheme heard this set of instructions.***

02B1.FrontAlarm.mp3

If you are about to have a frontal collision, you will hear this alarm sound:

- ***plays alarm.***

02B2.AfterFrontAlarm-BeforeRear.mp3

When you hear such an alarm,

You can either apply the brakes or swerve onto the sidewalk to avoid a frontal crash.

If you are about to have a rear collision, you will hear this alarm sound:

- ***plays alarm.***

02B04.AfterRearAlarm-BeforeLeft.mp3

When you hear such an alarm,

You can either Speed Up or swerve onto the sidewalk to avoid a rear crash.

If you drift out of your lane onto the left unintentionally, You will hear this alarm sound:

- ***plays alarm.***

02B06.AfterLeftLane-BeforeRight.mp3

When you hear such an alarm,

You should maintain control of the steering wheel and go back into your lane.

If you drift out of your lane onto the right unintentionally,

You will hear this alarm sound:

- ***plays alarm.***

AfterRightlane-fast

When you hear such an alarm,

You should maintain control of the steering wheel and go back into your lane.

Introduction – Continue

- ***Now, all participants will hear the same set of instructions from now.***

03.IntroductionCont.mp3

Please note that the alarms for the left and right lane deviation sound the same, but you have heard the left alarm through the left speaker, and the right alarm through the right speaker.

Please keep in mind that when you hear a warning sound, it may also just be a false alarm.

The drive is divided into 5 sessions -

3 training sessions, and 2 testing sessions.

At all times during your journey, please stay on the main road without turning off at intersections.

You will hear additional instructions for the training sessions before we begin the testing sessions.

Do you have any questions?

Speedlimit.mp3

If you look at the speedometer, the numbers above represent speed in miles per hour, and the numbers below represent speed in kilometers per hour.

Speed limits are given in miles per hour.

Throttle.mp3

Please make use of the practice sessions to get used to the throttle and breaking sensitivities of the car.

Practice Session Instructions

04.FirstTraining.mp3

You will now begin your training sessions.

The training sessions will not be scored, so take your time driving, maintain the posted speed limit, and follow any traffic control signs or signals.

During your drive, you will experience windy conditions.

When that happens, you may **unintentionally** drift out of your own lane. You will hear an alarm sound, and simply steer back onto your lane.

If you feel uncomfortable in any way, stop driving, close your eyes, and speak with the research assistant.

Please make sure the steering wheel is straight and your foot is off the accelerator and brake.

Soon you will see an image of a road in front of you.

When you see that image, begin driving by pressing the gas pedal.

Do you have any questions?

- ***STARTS FIRST PRACTICE SCENARIO***

05a.FirstEnd-AlarmQuiz.mp3

You have just completed the first training session.

- ***Ends here for single alarm scenarios, continues for multiple alarm scenarios.***

Before the next training session begins, you will do a little quiz on the alarms.

You will hear an alarm sound, and after that, please say out loud what alarm you think that was for: A frontal collision, a rear collision, a left lane drift, or a right lane drift.

- ***Plays alarms until he gets the quiz right*** reminder.mp3

Please be reminded of the following:

Firstly, if you see a potential rear collision, please jam the throttle and speed up or swerve onto the sidewalk.

Secondly, if you see a potential frontal collision, please jam the brakes or swerve onto the sidewalk.

Thirdly, please do not speed. You should monitor your speed from time to time, as the simulator does not give a good impression of speed.

Lastly, please stop right at the stop sign and right at the traffic light, and not before.

05a.SecondTraining.mp3

Now that you recognize the alarms, we will begin the next training session.

For this next training sessions and subsequent driving to come, you will hear music playing through the radio but you are not allowed to have a choice of stations.

Please make sure the steering wheel is straight and your foot is off the accelerator and brake.

Do you have any questions?

- ***STARTS SECOND PRACTICE SCENARIO***

05a. SecondEnd-TryTask-TaskInstructions.mp3

You have just completed the second training session.

For this next training scenario, you will be asked to complete a task while driving.

Your responses to the task will be recorded for scoring purposes.

Let's try the task.

You are now going to be asked to use the screen to your right to complete the next task.

You will see 7 numbers in succession on the screen, of which there will be 6 zeros and 1 other non-zero number.

Your task is to do math addition, adding up the position of the non-zero number, and the number itself.

You will use the number keys on the number pad, to respond.

For example, if you see 0 2 0 0 0 0 0 displayed on the screen, the correct answer is the total sum of the non-zero number, 2, and its position, 2, which equals 4.

You will enter 4 on the number key pad as the right answer.

However, if you see 0 5 0 0 0 0 0, the correct answer is the total sum of the non-zero number 5, and its position 2, which equals 7.

You will enter 7 on the number key pad as the right answer.

The task will occur at points during your drive.

Once you complete the task, please look ahead to the screen in front, and continue driving.

Your score will be computed at the end of each drive, on a percentage scale.

Let's practice this task.

Do you have any questions?

- ***Practice Secondary Task***

05a.Prac3Intro.mp3

Now that you recognize the alarms, we will begin the next training session.

You will drive through the last training session and perform this task at the same time.

Prac3-Fast.mp3

The task is designed to be difficult for everyone. That is, everyone will not be able to answer every question correctly and maintain good driving at the same time.

Please keep in mind that your primary job is always to maintain safe driving

Take your time driving, maintain the posted speed limit, and follow any traffic control signs or signals.

If you feel uncomfortable in any way, stop driving, close your eyes, and speak with the research assistant.

Please make sure the steering wheel is straight and your foot is off the accelerator and brake.

After this training session, you will hear additional instructions, before you begin the testing segments.

Do you have any questions?

- ***STARTS THIRD PRACTICE SCENARIO***

Testing Sessions Instructions

07.StartTesting.mp3

Now that you are familiar with the driving simulator, it is time to start the testing sessions.

07.StartTesting—MONEY - BREAK

You will earn $15 for completing the drive and up to an additional $10 bonus depending on your driving performance **and** your performance on the task that you just practiced.

Therefore, if you perform well, you will earn up to $25 today.

In addition, if you have the highest score in this experiment compared to other participants, you will get at $100 Amazon.com voucher.

You will be penalized $1 if you do not stop at a stop sign, or if you run a traffic light.

If your drive time exceeds 15 minutes, you will be penalized $1 for every minute that you arrive late.

However, you will be penalized $2 for every crash that occurs and $2 if you speed excessively during the drive.

During the drive, the speed limit is 55 miles per hour on most parts of your journey.

Like in real life, you are more likely to receive a ticket for going 80 miles per hour than for going 65 miles per hour on the journey.

You will have to monitor your own speed as you will not be pulled over for speeding and traffic violations.

Please note that you will be penalized **more** for crashes than for traffic violations and that you will be penalized **more** for speeding than for arriving late.

If you follow the posted speed limits, you will be able to complete your journey in time.

Before we start the next testing session, would you like to have a break?

reminder.mp3

Please be reminded of the following:

Firstly, if you see a potential rear collision, please jam the throttle and speed up or swerve onto the sidewalk.

Secondly, if you see a potential frontal collision, please jam the brakes or swerve onto the sidewalk.

Thirdly, please do not speed. You should monitor your speed from time to time, as the simulator does not give a good impression of speed.

Lastly, please stop right at the stop sign and right at the traffic light, and not before.

08.Testing1.mp3

You are about to begin a testing segment.

Your scores will be recorded for scoring purposes, and you will be penalized for crashes, traffic and speeding violations.

You will have to perform the task while driving, and will also be able to earn bonuses based on your performance.

Please keep in mind that your primary job is always to maintain safe driving

Remember not to turn off at intersections, and maintain the posted speed limit.

If you feel uncomfortable in any way, stop driving, close your eyes, and speak with the research assistant.

Please make sure the steering wheel is straight and your foot is off the accelerator and brake.

When you see the image of the road in front of you, you may begin by pressing the gas pedal.

Do you have any questions?

- ***STARTS FIRST TESTING SCENARIO***

09.InBetween.mp3

You have finished the first testing scenario.

Great job!

break.mp3

Before we start the next testing session, would you like to have a break?

10.Testing2.mp3

You are about to begin the last testing segment.

When you see the image of the road in front of you, you may begin by pressing the gas pedal.

Do you have any questions?

- ***STARTS SECOND TESTING SCENARIO***

11.END.mp3

You have now successfully completed the testing sessions.

Congratulations! We hope that you have enjoyed your drive.

You may now exit the car.

Appendix G

Participants filled out a post-experiment survey after they completed the testing sessions on a desktop computer and their answers were electronically stored. The survey questions are reproduced below:

Post-experiment survey

Hello and thank you for participating in the Driving Study conducted by Professor Mary L Cummings and Angela Ho.

Please fill out the following Post-Simulation Questionnaire. If you have any questions, please direct them to AngelaHo@mit.edu. Thank you.

Please fill in blanks or select the best response unless otherwise noted. Please answer all questions. Your answers to these questions will be held confidential.

Please do NOT discuss the contents of the experiment with anyone as the experiment is still on-going. Thank you.

1. What is your subject ID (Part1)?*
   Please ask the research assistant for your Subject ID. ___________
2. What is your Subject ID (Part2)*
   Please ask the Research Assistant for your Subject ID (part2) S __ M__

HEALTH

3. What kind of emotions did you feel while you were driving through the simulation scenarios?

	I did not feel this at all.	I felt this somewhat.	Describes exactly how I felt
Challenge			
Enjoyment			
Boredom			
Stress			
Frustration			

4. Do you feel unwell right now or during the simulated drive? Yes No

5. If you answered "Yes to the previous question, how well does each of the following describe how you feel now?

	I do not feel this at all.	I feel/felt this somewhat	Describes exactly how I feel/felt.
Nausea	0	1	2
Headache	0	1	2
Eye Strain	0	1	2
Drowsy	0	1	2
Dizzy	0	1	2

6. At which point during the experiment did you start to feel unwell and experienced the above-mentioned symptoms?

____

ALARMS

7. While driving, did you think that the alarms gave you timely alert in order to:
   a. Avoid a Frontal collision Yes No
   b. Avoid a Rear Collision Yes No
   c. keep in your own lane (left and right) Yes No

8. In what ways were the alarms helpful and/or not helpful in the above situations?

____

____

____

9. When you heard the alarm for the following conditions, did you know what triggered the alarm?

   a. Alarm warning of a Frontal collision Yes No
   b. Alarm warning of a Rear Collision Yes No
   c. Alarm warning of a Lane Drift Yes No

10. If you answered "no" to any part of question 9, why not?

____

____

11. While driving, you encountered many False Alarms – alarms that went off for apparently no reason. Under the conditions listed below, when you heard such an alarm, were you able to recognize if it was a False Alarm?*

a.	Alarm warning of a Frontal collision	Yes	No
b.	Alarm warning of a Rear Collision	Yes	No
c.	Alarm warning of a Left lane drift	Yes	No
d.	Alarm warning of a Right lane drift	Yes	No

12. If you answered "no" to any part of question 11, why not?

____

____

____

13. If the alarms were not helpful to you, and/or if they also induced a negative emotive response, please elaborate on what these responses were.

If you did NOT think that the alarms were unhelpful, you do NOT need to answer this question.

Emotive Responses	Frontal Collision Alarm	Rear Collision Alarm	Left Lane Drift Alarm	Right Lane Drift Alarm
Ineffective - You saw the event before you heard the alarms, but the alarms didn't affect you negatively.				
Annoying - The alarms were not helpful and you wished that you turn them off.				
Stressed - In addition to the impending collision, you were stressed by the alarms.				
Distracting - In addition to being unhelpful, they adversely affected your driving.				

14. Would you prefer the same warning alarm for all 4 types of events, or different alarms for each of the types of events?

_____Same _____Different

15. What type of alarms do you think that you would have preferred for the following conditions?

	Beeps	Generic Voice Alert ("danger" or "hazard" etc)	Specific Voice Alert ("front", "rear" etc)	Others
Alarm warning of a frontal collision				
Alarm warning of a rear collision				
Alarm warning of a Left lane drift				

Alarm warning of a Right lane drift				

16. If you answered “other” to any part of the question above, please elaborate.

PRACTICE & TESTING SCENARIOS

17. While driving through the test scenarios, were there instances where you saw the following condition happening, but was waiting to hear the alarm before you took an aversive action?*

Frontal Collision	Yes	No
Rear Collision	Yes	No
Left Lane Drift	Yes	No
Right Lane Drift	Yes	No

18. Did you have enough practice time for the following before the actual testing scenarios?*

Getting used to the throttle, brakes, and steering of the car	Yes	No
Understanding the number task	Yes	No
Knowing what the alarms meant	Yes	No

19. Did you think that the length of the actual TESTING scenarios were:

1st testing -	Too short	Too long	Just Right
2nd testing -	Too short	Too long	Just Right

20. Did you find the number task challenging enough to perform, while maintaining safe driving at the same time?*

Yes No

Comments

21. Do you have any comments /constructive criticisms /ideas/suggestions for improvements on the:

Practice scenarios?

Testing scenarios?

How the experiment was conducted, in terms of experimenter’s conduct and overall experience?

This survey in terms of format, clarity, and succinctness of questions asked, and length?

Any other comments?

Appendix H

Performance Bonus Calculation

. This $5 bonus was performance based and money would be deducted based on the number of traffic violations such as running traffic lights and speeding, the number of collisions and roadway departures off the shoulder as well as driving over the allotted time of 15 minutes. The $5 bonus also took into account their score on the secondary task on both Scenario A and B. Thus, the bonus gave participants an incentive to "perform well," which was weighted across safe driving (no collisions), keeping within speeding limits, following traffic laws, and performing well on the secondary task. Additionally, participants were not encouraged to drive too slowly as the bonus would be affected if they went over the allotted time of 15 minutes too. Throughout the driving scenarios, there are speeding limits with signs put up intermittently along the road. Participants were defined to be speeding if they drove over the speed limit for that particular section for more than 5 seconds.

Appendix I

GLM Analysis: SPSS Output

LEGEND: The three factors are:

- "Alarm", or alarm alerting scheme (i.e., master vs. single)
- "direct", or direction or driver warning systems (i.e., FCW, FVFA, Left LDW, Right LDW)
  - "1" represents FCWS condition
  - "2" represents FVFA condition
  - "3" represents Left LDWS condition
  - "4" represents Right LDWS condition
- "Reliab" or reliability (i.e., high vs. low)
  - "1" represents the high reliability condition
  - "2" represents the low reliability condition

Statistics for Reaction Time Data

Descriptive Statistics

	Alarm type	Mean	Std. Deviation	N
High reliability FCW	Multiple	.4568	.13741	20
	single	.5016	.12948	20
	Total	.4792	.13371	40
High reliability FVFA	Multiple	1.5080	.65030	20
	single	1.5004	.61452	20
	Total	1.5042	.62451	40
High reliability Left LDW	Multiple	1.0660	.10652	20
	single	1.1209	.11081	20
	Total	1.0935	.11083	40
High reliability Right LDW	Multiple	.9789	.11208	20
	single	1.0205	.08313	20
	Total	.9997	.09965	40
Low reliability FCW	Multiple	.5197	.52044	20
	single	.3279	.25292	20
	Total	.4238	.41540	40
Low reliability FVFA	Multiple	1.9764	.89893	20
	single	1.9248	.85890	20
	Total	1.9506	.86819	40
Low reliability Left LDW	Multiple	1.1443	.11154	20
	single	1.2280	.16087	20
	Total	1.1861	.14305	40
Low reliability Right LDW	Multiple	.977	.1115	20
	single	1.006	.1652	20
	Total	.991	.1398	40

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
reliabi	Sphericity Assumed	1.129	1	1.129	9.694	.004
	Greenhouse-Geisse	1.129	1.000	1.129	9.694	.004
	Huynh-Feldt	1.129	1.000	1.129	9.694	.004
	Lower-bound	1.129	1.000	1.129	9.694	.004
reliabi * Alarm	Sphericity Assumed	.088	1	.088	.751	.391
	Greenhouse-Geisse	.088	1.000	.088	.751	.391
	Huynh-Feldt	.088	1.000	.088	.751	.391
	Lower-bound	.088	1.000	.088	.751	.391
Error(reliabi)	Sphericity Assumed	4.427	38	.117		
	Greenhouse-Geisse	4.427	38.000	.117		
	Huynh-Feldt	4.427	38.000	.117		
	Lower-bound	4.427	38.000	.117		
direct	Sphericity Assumed	65.986	3	21.995	91.244	.000
	Greenhouse-Geisse	65.986	1.259	52.419	91.244	.000
	Huynh-Feldt	65.986	1.316	50.140	91.244	.000
	Lower-bound	65.986	1.000	65.986	91.244	.000
direct * Alarm	Sphericity Assumed	.246	3	.082	.341	.796
	Greenhouse-Geisse	.246	1.259	.196	.341	.613
	Huynh-Feldt	.246	1.316	.187	.341	.622
	Lower-bound	.246	1.000	.246	.341	.563
Error(direct)	Sphericity Assumed	27.481	114	.241		
	Greenhouse-Geisse	27.481	47.835	.574		
	Huynh-Feldt	27.481	50.009	.550		
	Lower-bound	27.481	38.000	.723		
reliabi * direct	Sphericity Assumed	3.091	3	1.030	8.559	.000
	Greenhouse-Geisse	3.091	1.469	2.104	8.559	.002
	Huynh-Feldt	3.091	1.554	1.989	8.559	.001
	Lower-bound	3.091	1.000	3.091	8.559	.006
reliabi * direct * Alar	Sphericity Assumed	.207	3	.069	.573	.634
	Greenhouse-Geisse	.207	1.469	.141	.573	.516
	Huynh-Feldt	.207	1.554	.133	.573	.525
	Lower-bound	.207	1.000	.207	.573	.454
Error(reliabi*direct)	Sphericity Assumed	13.726	114	.120		
	Greenhouse-Geisse	13.726	55.831	.246		
	Huynh-Feldt	13.726	59.052	.232		
	Lower-bound	13.726	38.000	.361		

Levene's Test of Equality of Error Variances[a]

	F	df1	df2	Sig.
High reliability FCW	.876	1	38	.355
High reliability FVFA	.010	1	38	.920
High reliability Left LDW	.133	1	38	.717
High reliability Right LDW	.427	1	38	.517
Low reliability FCW	3.815	1	38	.058
Low reliability FVFA	.121	1	38	.730
Low reliability Left LDW	.458	1	38	.503
Low reliability Right LDW	.394	1	38	.534

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a.

Design: Intercept+Alarm
Within Subjects Design: reliabi+direct+reliabi*direct

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	372.244	1	372.244	1707.048	.000
Alarm	8.26E-006	1	8.26E-006	.00004	.995
Error	8.286	38	.218		

Estimated Marginal Means

1. Alarm type

Measure: MEASURE_1

			95% Confidence Interval	
Alarm type	Mean	Std. Error	Lower Bound	Upper Bound
Multiple	1.078	.037	1.004	1.153
single	1.079	.037	1.004	1.153

Pairwise Comparisons

Measure: MEASURE_1

(I) Alarm type	(J) Alarm type	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Multiple	single	.000	.052	.995	-.106	.105
single	Multiple	.000	.052	.995	-.105	.106

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

2. reliabi

Measure: MEASURE_1

reliabi	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.019	.026	.966	1.072
2	1.138	.037	1.062	1.214

Pairwise Comparisons

Measure: MEASURE_1

(I) reliabi	(J) reliabi	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.119*	.038	.004	-.196	-.042
2	1	.119*	.038	.004	.042	.196

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

3. direct

Measure: MEASURE_1

direct	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.452	.034	.382	.521
2	1.727	.100	1.524	1.931
3	1.140	.017	1.105	1.175
4	.995	.014	.967	1.024

Pairwise Comparisons

Measure: MEASURE_1

(I) direct	(J) direct	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-1.276*	.105	.000	-1.489	-1.063
	3	-.688*	.039	.000	-.767	-.610
	4	-.544*	.034	.000	-.612	-.476
2	1	1.276*	.105	.000	1.063	1.489
	3	.588*	.108	.000	.368	.807
	4	.732*	.101	.000	.528	.936
3	1	.688*	.039	.000	.610	.767
	2	-.588*	.108	.000	-.807	-.368
	4	.144*	.023	.000	.098	.191
4	1	.544*	.034	.000	.476	.612
	2	-.732*	.101	.000	-.936	-.528
	3	-.144*	.023	.000	-.191	-.098

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

4. Alarm type * reliabi

Measure: MEASURE_1

Alarm type	reliabi	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Multiple	1	1.002	.037	.927	1.078
	2	1.154	.053	1.047	1.261
single	1	1.036	.037	.961	1.111
	2	1.122	.053	1.014	1.229

5. Alarm type * direct

Measure: MEASURE_1

Alarm type	direct	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Multiple	1	.488	.049	.390	.587
	2	1.742	.142	1.455	2.030
	3	1.105	.025	1.055	1.155
	4	.978	.020	.937	1.019
single	1	.415	.049	.316	.513
	2	1.713	.142	1.425	2.000
	3	1.174	.025	1.125	1.224
	4	1.013	.020	.972	1.054

6. reliabi * direct

Measure: MEASURE_1

reliabi	direct	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	.479	.021	.436	.522
	2	1.504	.100	1.302	1.707
	3	1.093	.017	1.059	1.128
	4	1.000	.016	.968	1.031
2	1	.424	.065	.293	.555
	2	1.951	.139	1.669	2.232
	3	1.186	.022	1.142	1.230
	4	.991	.022	.946	1.036

7. Alarm type * reliabi * direct

Measure: MEASURE_1

Alarm type	reliabi	direct	Mean	Std. Error	95% Confidence Interval	
					Lower Bound	Upper Bound
Multiple	1	1	.457	.030	.396	.517
		2	1.508	.141	1.222	1.794
		3	1.066	.024	1.017	1.115
		4	.979	.022	.934	1.024
	2	1	.520	.091	.334	.705
		2	1.976	.197	1.578	2.374
		3	1.144	.031	1.082	1.207
		4	.977	.032	.913	1.041
single	1	1	.502	.030	.441	.562
		2	1.500	.141	1.214	1.787
		3	1.121	.024	1.072	1.170
		4	1.020	.022	.976	1.065
	2	1	.328	.091	.143	.513
		2	1.925	.197	1.527	2.323
		3	1.228	.031	1.165	1.291
		4	1.006	.032	.942	1.069

Statistics for Response Accuracy Data

Variables not in the Equation

			Score	df	Sig.
Step 0	Variables	scheme(1)	.251	1	.616
		type	14.121	3	.003
		type(1)	2.558	1	.110
		type(2)	5.699	1	.017
		type(3)	.981	1	.322
		reliability	547.997	1	.000
		reliability * type	15.072	3	.002
		reliability by type(1)	1.499	1	.221
		reliability by type(2)	9.228	1	.002
		reliability by type(3)	.128	1	.721
		scheme * type	3.519	3	.318
		scheme(1) by type(1)	.267	1	.605
		scheme(1) by type(2)	.585	1	.444
		scheme(1) by type(3)	1.481	1	.224
		reliability by scheme(1)	.091	1	.764
	Overall Statistics		567.093	12	.000

Statistics for Secondary Dependent Variables: Number of Collisions and Secondary Task Performance

Legend:

- Ascore: Score on Secondary Task under High reliability condition
- Bscore: Score on Secondary Task under Low reliability condition
- Acritical: Number of collisions under High reliability condition
- Bcritical: Number of collisions under Low reliability condition

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
Bscore - Ascore	Negative Ranks	12[a]	16.04	192.50
	Positive Ranks	22[b]	18.30	402.50
	Ties	6[c]		
	Total	40		
Bcritical - Acritical	Negative Ranks	26[d]	15.54	404.00
	Positive Ranks	6[e]	20.67	124.00
	Ties	8[f]		
	Total	40		

a. Bscore < Ascore

b. Bscore > Ascore

c. Bscore = Ascore

d. Bcritical < Acritical

e. Bcritical > Acritical

f. Bcritical = Acritical

Test Statistics[c]

	Bscore - Ascore	Bcritical - Acritical
Z	-1.798[a]	-2.696[b]
Asymp. Sig. (2-tailed)	.072	.007

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

Mann-Whiteney Test

Ranks

	alarmtype	N	Mean Rank	Sum of Ranks
Ascore	multiple	20	21.23	424.50
	single	20	19.78	395.50
	Total	40		
Bscore	multiple	20	16.90	338.00
	single	20	24.10	482.00
	Total	40		
Acritical	multiple	20	20.03	400.50
	single	20	20.98	419.50
	Total	40		
Bcritical	multiple	20	21.70	434.00
	single	20	19.30	386.00
	Total	40		

Test Statistics[b]

	Ascore	Bscore	Acritical	Bcritical
Mann-Whitney U	185.500	128.000	190.500	176.000
Wilcoxon W	395.500	338.000	400.500	386.000
Z	-.395	-1.968	-.274	-.856
Asymp. Sig. (2-tailed)	.693	.049	.784	.392
Exact Sig. [2*(1-tailed Sig.)]	.698[a]	.052[a]	.799[a]	.529[a]

[a] Not corrected for ties.

[b] Grouping Variable: alarmtype

Bibliography

[1] U.S. Department of Transportation, "Intelligent Vehicle Initiative's Mission: Prevention of Highway Crashes and the Fatalities and Injuries They Cause," Website, 2005.

[2] U.S. Department of Transportation, "Major Initiatives: Integrated Vehicle Based Safety Systems," Website, 2006.

[3] NHTSA, DOT, "Automotive Collision Avoidance System (ACAS) Program/First Annual Report," HS 809 080, August 2000.

[4] C. Barnden, *Vehicle Safety Systems Get Active*, vol. 13, 8 ed, ITS America News, August 2003.

[5] J. W. Runge, "What is VII?," presented at VII (Vehicle Infrastructure Integration) Public Meeting, San Francisco CA, 2005.

[6] BNA Inc, "New Technologies Cutting-Edge Vehicle Technologies Address Vehicle Mismatch; Pedestrian, Cyclist Safety," Product Safety and Liability, 26 September, 2005.

[7] M. Matlz, H. Sun, Q. Wu, and R. Mourant, "Use of In-Vehicle Alerting System for Older and Younger Drivers: Does Experience Count?," in *83rd Annual Meeting of the Transportation Research Board*. Washington, D.C., 2004.

[8] J. D. Lee, J. D. Hoffman, and E. Hayes, "Collision Warning Design To Mitigate Driver Distraction," in *SIGCHI Conference on Human Factors in Computing Systems*. Vienna, Austria, 2004.

[9] R. Graham, "Use of Auditory Icons as Emergency Warnings: Evaluation within a Vehicle Collision Avoidance Application," *Ergonomics*, vol. 42, pp. 1233-1248, 1999.

[10] L. Tijerina, S. Johnston, E. Parmer, H. A. Pham, M. D. Winterbottom, and F. S. Barickman, "Preliminary Studies in Haptic Displays for Rear-end Collision Avoidance System and Adaptive Cruise Control Application," National Highway Traffic Safety Administration, U.S. Department of Transportation, DOT-HS-809-151, 2000.

[11] General Motors Corporation, Delphi & Delco Electronic Systems, National Highway Traffic Safety Administration, U.S. Department of Transportation, "Automotive Collision Avoidance Operational Field Test Warning Cue Implementations Summary Report," Report, DOT-HS-809-462, May 2002.

[12] V. A. W. J. Marchau and W. W. Walker, "Dealing with uncertainty in implementing Advanced Driver Assistance Systems: An Adaptive Approach," *Integrated Assessment*, vol. 4, pp. 35-45, 2003.

[13] L. Bainbridge, "Ironies of Automation," *Automatica*, vol. 19, pp. 775-779, 1983.

[14] P. A. Hancock and R. Parasuraman, "Human factors and safety in the design of intelligent Vehicle-Highway Systems (IVHS)." *Journal of Safety Research*, vol. 23, 4, Winter, pp. 181-198, 1992.

[15] W. König and H. Mutschler, "Technical Report: MMI of warning systems in vehicles," ISO-TC22.SC13/WG8, 2003.

[16] Integrated Project PReVENT, "About Preventive Safety - Introduction," 2006.

[17] ITS Joint Program Office, U.S. Department Of Transportation, "Intelligent Transportation Systems - Applications Overview," Website, 2006.

[18] U.S. Department of Transportation, "Intelligent Vehicle Initiative Final Report," Report, September 2005.

[19] General Motors Corporation, National Highway Traffic Safety Administration, U.S. Department of Transportation, "Automotive Collision Avoidance System Field Operational Test (ACAS FOT) Final Program Report," Report, DOT-HS-809-886, March 2005.

[20] U.S. Department of Transportation, "Integrated Vehicle Based Safety Systems: Technologies Involved," Website, 2006.

[21] U.S. Department Of Transportation, "Integrated Vehicle Based Safety Systems: Examples & Scenarios," Website, 2006.

[22] M. R. Endsley, "Design and evaluation for situation awareness enhancement," presented at Proceedings of the Human Factors Society 32nd Annual Meeting, Santa Monica, CA, 1988.

[23] P. Burns, "International Harmonized Research Activities - Intelligent Transport Systems (IHRAITS) Working Group Report," in *19th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Washington D.C.: Transport Canada, 2005.

[24] O. M. J. Carsten and L. Nilsson, "Safety assessment of driver assistance systems," *European Journal of Transport and Infrastructure Research*, vol. 1, pp. 225-243, 2001.

[25] L. Bainbridge, "Ironies of Automation," in *New Technology and Human Error*, J. Rasmussen, K. Duncan, and J. Leplat, Eds. Chichester and New York: John Wiley & Sons, 1987.

[26] TNO Inro, Delft, The Netherlands, "Deployment scenarios for advanced driver assistance systems," Report Inro/VK 1999-07, 1999.

[27] S. Becker, T. Johanning, J. Feldges, and M. Kopf, "The Integrated Approach of User, System and Legal Perspective: Final Report on Recommendations for Testing and Market Introduction of ADAS," Response, Commission of the European Communities, Directorate General XIII, Project TR4022, Deliverable No. D2.2, 2000.

[28] T. B. Sheridan and W. Verplank, *Human and Computer Control of Undersea Teleoperators*. Cambridge, MA, Man-Machine Systems Laboratory, Department of Mechanical Engineering, MIT, 1978.

[29] N. D. Lerner, B. M. Kotwal, R. D. Lyons, and D. J. Gardner-Bonneau, "Preliminary human factors guidelines for crash avoidance warning devices.," National Highway Traffic Safety Administration, U.S. Department of Transportation, DOT-HS-808-342, January 1996.

[30] C. M. Johnson, "The National ITS Program: Where We've Been and Where We're Going," in *Public Roads On-Line*, vol. 61, 1997.

[31] P. Clarke, "Adaptive cruise control takes to the highway," in *EETimes Online*. Amsterdam, 1998.

[32] Toyota, "Toyota's ITS Vision - Toyota's ITS History," Website, Japan, 2006.

[33] Research and Markets, "An Introduction To Advanced Driver Assistance Systems in Europe," Market Report, 2004.

[34] E. Llaneras and L. Neurauter, "Early Adopters Safety-Related Driving With Advanced Technologies - 2005 Inventory of In-Vehicle Devices & Interfaces Characteristics," Virginia Tech Transportation Institute, Task Order 10 under Project DTNH22-99-D-07005, 2005.

[35] Y. Goi, Y. Kondo, I. Nishimura, T. Mimuro, K. Yamamoto, and Y. Chikatani, "Towards Enhanced Safety - Technology Innovation and Future Efforts," in *Mitsubishi Motors Technical Review: Technical Perspective*, 2002.

[36] Valeo, "Valeo's revolutionary Lane Departure Warning System makes debut on Nissan Infiniti vehicles," in *Valeo Press Release*. Paris, France, 2004.

[37] Infinity, "Advanced Lane Departure Warning System to Debut on 2005 Infiniti FX and 2006 Infiniti M45," in *Business Wire*. Gardena, California, 2004.

[38] Mitsubishi Motors Corporation, "Development of lane departure warning system," 2001.

[39] Volvo, "Volvo Car Corporation: Moving into the Third Age of safety," November 22 2005.

[40] C. D. Wickens, *Engineering Psychology and Human Performance*. New York, HarperCollins Publishers, Inc, 1992.

[41] M. C. Polson and A. Friedman, "Task-sharing within and between hemispheres: a multiple-resources approach," *Human Factors*, vol. 30, pp. 633-643, 1988.

[42] W. W. Wierwille, *Visual and manual demands of in-car controls and displays*. London, Washington D.C., Taylor & Francis, 1993.

[43] C. D. Wickens, D. Sandry, and M. Vidulich, "Compatibility and resource competition between modalities of input, central processing, and output," *Human Factors*, vol. 25, pp. 227-248, 1983.

[44] C. W. Telford, "The refractory phase of voluntary and associative responses," *Journal of Experimental Psychology*, vol. 14, pp. 1-36, 1931.

[45] D. Chiang, E. Llaneras, and J. Foley, "Driving Simulator Investigation of Multiple Collision Alarm Interference Issues," presented at DSC Asia/Pacific 2006, Tsukuba, Japan, May-June 2006.

[46] V. L. Neale and T. A. Dingus, "Motor Vehicle Warnings," in *Handbook of Warnings*, M. S. Wogalter, Ed. Mahwah, NJ: Lawrence Erlbaum Associates 2006.

[47] R. Llaneras, N. Lerner, T. Dingus, and J. Moyer, "Attention Demand of IVIS Auditory Displays: An On-Road Study under Freeway Environments.," presented at 14th Congress of International Ergonomics Association, Santa Monica, CA, 2000.

[48] Y.-C. Liu, "Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveller information systems," *Ergonomics*, vol. 44, pp. 425-442, 2001.

[49] T. A. Dingus, D. V. McGehee, N. Manakkal, S. K. V. Jahns, C., and J. M. Hankey, "Human factors field evaluation of automotive headway maintenance/collision warning devices," *Human Factors*, vol. 39, pp. 216-229, 1997.

[50] J. D. Lee and K. A. See, "Trust in Automation: Designing for Appropriate Reliance," *Human Factors*, vol. 46, pp. 50-80, 2004.

[51] R. Parasuraman and V. Riley, "Humans and Automation: Use, Misuse, Disuse, Abuse," *Human Factors*, vol. 39, pp. 230-253, 1997.

[52] M. S. Young and N. A. Stanton, *What's Skill Got to Do with It? Vehicle Automation and Driver Mental Workload*, 1998.

[53] H. Zhang and M. Smith, "SAfety VEhicles using Adaptive Interface Technology: A Literature Review of Visual Distraction Research," Delphi Electronics & Safety, 2004.

[54] J. L. Campbell, B. L. Hooey, C. Carney, R. J. Hanowski, B. F. Gore, and B. H. Kantowitz, "Investigation of alternative displays for side collision avoidance systems," National Highway Traffic Safety Administration, U.S. Department of Transportation, DOT-HS-808-579, 1996.

[55] H. Uno, K. Hiramatsu, H. Ito, B. Atsumi, and M. Akamatsu, "Detectability of Criticality and Urgency under Various Conditions of Visual and Auditory Indications," presented at 4th World Congress on Intelligent Transport Systems, Brussels, Belgium, 1997.

[56] K. A. Brookhuis, D. De Waard, and W. H. Janssen, "Behavioral Impacts of Advanced Driver Assistance Systems - an Overview," *European Journal of Transport and Infrastructure Research*, vol. 1, pp. 245-253, 2001.

[57] T. C. Lansdown, "Visual allocation and the availability of driver information," in *Traffic and Transport Psychology: Theory and Application*, T. Gothengater and E. Carbonell, Eds. Amsterdam: Pergamon, 1997, pp. 215-223.

[58] M. S. Sanders and E. J. McCormick, *Human Factors in Engineering and Design*, 7th ed. New York, McGraw Hill, 1993.

[59] W. B. Verwey, "Adaptive interface based on driver resource demands," presented at Designing for everyone, 11th Congress of the International Ergonomics Association, Paris, France, 1991.

[60] Y. Xiao and F. J. Seagull, "An analysis of problems with auditory alarms: Defining the roles of alarms in process monitoring tasks," presented at Human Factors and Ergonomics 43rd Annual Meeting, Santa Monica, CA, 1999.

[61] R. D. Patterson, "Auditory warning sounds in the work environment," *Philosophical Transactions of the Royal Society London*, vol. B, pp. 485-492, 1990.

[62] R. Kiefer, D. LeBlanc, M. Palmer, J. Salinger, R. Deering, and M. Shulman, "Development and validation of functional definitions and evaluation procedures for collision warning/avoidance systems," National Highway Traffic Safety Administration, U.S. Department of Transportation, DOT-HS-808-964, 1999.

[63] University of Groningen, Traffic Research Center, "The impact of collision avoidance systems on driver behavior and traffic study: Preliminaries to studies within the GIDS Project," Tech Report Driver Project V1041, Netherlands, 1989.

[64] T. J. Doll and D. J. Folds, "Auditory signals in military aircraft: ergonomic principles versus practice," presented at IEEE National Aerospace and Electronics Conference, NAECON, Dayton, USA, 1985.

[65] O. Heller and H. P. Krüger, "Recommendations for the proposal ISO/TC22/SC13/WG8, Auditory information presentation," Interdisziplinäres Zentrum für Verkehrswissenschaften an der Universität Würzburg, Psychologisches Institut, March 22, 1996.

[66] M. Panou, M. Gemou, and E. Bekiaris, "Towards an integrated in-vehicle HMI for ADAS and its application for lateral collision warnings," presented at 1st FERSI Scientific Road Safety Research Conference, Germany, 7-8 September 2005.

[67] E. R. Mynatt, "Auditory presentation of graphical user interfaces," in *Auditory Display*, G. Kramer, Ed. Reading, PA: Addison-Wesley, 1994.

[68] S. M. Belz, G. S. Robinson, and J. G. Casali, "A New Class of Auditory Warning Signals for Complex Systems: Auditory Icons," *Human Factors*, vol. 41, pp. 608-608, 1999.

[69] T. Suetomi and T. Niibe, "A Human Interface Design of Multiple Collision Warning System," presented at 9th World Congress on Intelligent Transportation Systems, Chicago, IL, 2002.

[70] A. W. Bronkhorst, J. A. Veltman, and L. van Breda, "Applications of a three-dimensional auditory display in a flight task," *Human Factors* vol. 38, pp. 23-33, 1996.

[71] R. B. King and S. R. Oldfield, "The impact of signal bandwidth on auditory localisation: Implications for the design of three-dimensional displays," *Human Factors*, vol. 39, pp. 287-295, 1997.

[72] L. Nilsson, H. Alm, and W. Janssen, *Collision avoidance systems - effects of different levels of task allocation on driver behaviour*. The Netherlands, University of Groningen, Traffic Research Center, 1991.

[73] A. D. Horowitz and T. A. Dingus, "Warning signal design: a key human factors issue in an in-vehicle front-to-rear-end-collision warning system," presented at Human Factors Society 36th Annual Meeting, 1992.

[74] Society of Automotive Engineers, "Ergonomic aspects of electronic instrumentation: a guide for designers," SP-576, Warrendale, 1984.

[75] F. J. Getty, J. A. Swets, R. M. Pickett, and D. Gonthier, "System operator response to warnings of danger: a laboratory investigation of the effects of the predictive value of a warning on human response time," *Journal of Experimental Psychology: Applied*, vol. 1, 1995.

[76] A. R. Pritchett, "Pilot non-conformance to alerting system commands," presented at IEEE International Conference on Systems, Man, and Cybernetics. Computational Cybernetics and Simulation, Orlando, Florida, 1997.

[77] D. M. Usher, "The alarm matrix," in *Human Factors in Alarm Design*, N. Stanton, Ed. London: Taylor and Francis, 1994, pp. 139-146.

[78] E. L. Wiener, "Cockpit automation," in *Human Factors in Aviation*, E. L. Wiener and D. C. Nagel, Eds. San Diego, CA: Academic Press, 1988, pp. 433-461.

[79] M. Enriquez and K. E. MacLean, "Impact of haptic warning signal reliability in a time-and-safety-critical task," presented at 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004.

[80] A. W. L. Ho, M. L. Cummings, E. Wang, L. Tijerina, and D. Kochhar, "Integrating Intelligent Driver Warning Systems: Effects of Multiple Alarms and Distraction on

Driver Performance," presented at Transportation Research Board, Washington, D.C., 2006.

[81] J. Bliss and S. A. Acton, "Alarm mistrust in automobiles: how collision alarm reliability affects driving," *Applied Ergonomics*, vol. 34, pp. 499-509, 2003.

[82] E. E. Wiese and J. D. Lee, "Auditory Alerts for In-Vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance," *Ergonomics*, vol. 47, pp. 965-986, 2004.

[83] L. Song and J. K. Kuchar, "Describing, Predicting, and Mitigating Dissonance Between Alerting Systems," presented at 4th International Workshop on Human Error, Safety, and System Development, June 11-12, Linkoping, Sweden, 2001.

[84] H. N. Uno, K. and K. Hashimoto, "A Tentative Information Management Procedure to improve the usability of ITS Information for Drivers," presented at 8th World Congress on Intelligent Transportation Systems, Sydney, Australia, 2001.

[85] D. Woods, "The alarm problem and directed attention in dynamic fault management," *Ergonomics*, vol. 38, pp. 2371-2393, 1995.

[86] V. Marchau and R. Van der Heijden, "Policy aspects of driver support systems implementation: results of an international Delphi study," *Transport Policy*, vol. 5, pp. 249-258, 1998.

[87] T. J. Foxon, "Technological and Institutional 'Lock-In' as a Barrier to Sustainable Innovation," Imperial College Centre for Energy Policy and Technology (ICCEPT), 2002.

[88] R. Van der Heijden and V. Marchau, "Safety Impacts of Transport Telematics in Road Traffic, An Exploration of Certainties and Uncertainties," presented at 2nd World Congress on Safety of Transportation: Inbalance between Growth and Safety, Delft, Netherlands, 1998.

[89] T. B. Sheridan, *Humans and Automation: System Design and Research Issues*. New York, J Wiley & Sons, Wiley Series in System Engineering and Management, HFES Issues in Human Factors and Ergonomics Series, 2002.

[90] J. Hedlund, "Risky Business: safety regulations, risk compensation, and individual behavior," *Injury Prevention*, vol. 6, pp. 82-90, 2000.

[91] Committee on Trauma Research, Commission on Life Sciences, National Research Council and the Institute of Medicine, "Injury in America: a continuing public health problem," Washington D.C.: National Academic Press, 1985.

[92] Opinion Research Corporation, "Safety Belt Usage: Survey of Cars in the Traffic Population," Princeton, December 1978.

[93] D. Glassbrenner, "Safety Belt Use in 2005 - Use Rates in the States and Territories," National Highway Traffic Safety Administration, Department of Transportation, DOT HS 809 970, November 2005

[94] S. Peltzman, "The effects of automobile safety regulations," *Journal of Political Economy*, vol. 83, pp. 677-725, 1975.

[95] G. Wilde, "Critical issues in risk homeostasis theory," *Risk Analysis*, vol. 2, pp. 249-258, 1982.

[96] R. J. Arnould and H. Grabowski, "Auto Safety Regulation: An Analysis of Market Failure," *The Bell Journal of Economics*, vol. 12, pp. 27-48, 1981.

[97] National Highway Traffic Safety Administration, U.S. Department of Transportation "Part 571 Federal Motor Vehicle Safety Standards and Regulations, Crashworthiness," Website, 2006.

[98] A. Parkes, "The contribution of human factors guidelines and standards to usable and safe in-vehicle systems," in *Smart Vehicles*, J. P. Pauwelussen and H. B. Pacejka, Eds. Lisse, The Netherlands: Swets & Zeitlinger, 1995, pp. 393-402.

[99] European Commission, "Distribution and Servicing of Motor Vehicles in the European Union," Brussels, 2002.

[100] Commission of the European Communities, "DRIVE Safety Task Force: Guidelines On Traffic Safety, Man-Machine Interaction and System Safety," Report, DG XIII, Brussels, 1991.

[101] Department of Transportation, Federal Aviation Administration, "Auditory alarms in the airway facilities environment," DOT/FAA/CT-TN04/04, November 2003.

[102] DOT/FAA Systems research and development service, "Aircraft alerting systems criteria study," FAA-RD-76-222, Washington D.C., 1977.

[103] R. Van der Heijden and K. Van Wees, "Introducing Advanced Driver Assistant Systems: Legal Issues," *European Journal of Transport and Infrastructure Research*, vol. 1, pp. 309-326, 2001.

[104] N. A. Ashford, C. Ayers, and R. T. Stone, "Using Regulation to Change the Market for Innovation," *Harvard Environmental Law Review*, vol. 9, pp. 419-466, 1995.

[105] P. Green, "Why Safety and Human Factors/Ergonomics Standards are so Difficult to Establish," in *Human Factors in Transportation, Communication, Health and the Workplace*, D. d. Waard, K. A. Brookhuis, J. Moraal, and A. Toffetti, Eds. Maastricht, The Netherlands: Shaker Publishing, 2002.

[106] K. Young, M. Regan, and M. Hammer, "Driver Distraction: A Review of the Literature," Monash University Accident Research Centre, Report No. 206, 2003.

[107] Ho, A.W.L. and M.L. Cummings, "Multiple Alarms and Driver Situational Awareness," HAL2005-01, Cambridge, MA: MIT Humans and Automation Laboratory, 2005.

[108] C. M. Rudin-Brown and H. A. Parker, "Behavioral adaptation to adaptive cruise control (ACC): implications for preventive strategies," *Transportation Resarch Part F Traffic Psychology and Behavior*, vol. 7, pp. 59-76, 2004.

[109] N. Gupta, A. M. Bisantz, and T. Singh, "The effects of adverse condition warning system characteristics on driver performance: an investigation of alarm signal type and threshold level," *Behavior and Information Technology*, vol. 12, pp. 235-348, 2002.

[110] A. D. Andre and C. D. Wickens, "When users want what's not best for them," in *Ergnomics in design; the magazine of human factors applications*, 1995.

[111] A. Tversky and D. Kahneman, "Judgment Under Uncertainty: Heuristics and Biases," *Science*, pp. 1124-1131, 1974.

[112] J. M. Wetmore, "Redefining Risks and Redistributing Responsibilities: Building Networks to Increase Automobile Safety," *Science, Technology and Human Values*, vol. 29, pp. 377-405, 2004.

[113] "Occupant Protection (Federal Register, Title 49, Part 571)," 1995.

[114] "National Traffic and Motor Vehicle Act," in *15 U.S.C.A.* , vol. Ch. 38 80 Stat. 718, 1996.

[115] W. Boulering and D. Purohit, "The Price of Safety," *The Journal of Consumer Research*, vol. 23, pp. 12-25, 1996.

[116] F. Mannering and C. Winston, "Automobile Air Bags in the 1990s: Market Failure or Market Efficiency?," *Journal of Law and Economics*, vol. 38, pp. 265-279, 1995.

[117] National Highway Traffic Safety Administration, Department of Transportation, "Federal Motor Vehicle Safety Standards, Occupant Crash Protection, 49 CFR Parts 552, 571, 585 and 595," Docket No. NHTSA 00-7013; Notice 1, RIN 2127-AG70.

[118] "Airbags-The Next Generation," IHS The Source for Critical Information and Insight - Automotive Industry Trends, Website.

[119] Society of Automotive Engineers, "SAE J2399 - Adaptive Cruise Control (ACC) Operating Characteristics and User Interface," 2003.

[120] Society of Automotive Engineers, "SAE J2400 - Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements," 2003.

[121] European Commission, "Recommendation of the Commission of the European Communities to the Member States and Industry on Safe and Efficient In-Vehicle Information and Communication Systems: A European Statement of Principles on Human Machine Interface," Brussels, 2000.

[122] N. Komoda and R. W. Goudy, "The Standardization Activities in ISO/TC204/WG14, Vehicle/Roadway Warning and Control Systems," presented at Proceedings of 2nd World Congress on Intelligent Transport Systems, Tokyo, Japan, 1995.

[123] Society of Automotive Engineers, "Working Group 14 - Vehicle/Roadway Warning and Control Systems," ISO/TC204, 2006.

[124] G. A. Akerlof, "The Market for Lemons: Quality Uncertainty and Market Mechanism," *Quarterly Journal of Economics*, vol. 84, pp. 488-500, 1970.

[125] G. J. Stigler, "The Theory of Economic Regulation," *The Bell Journal of Economics and Management Science*, vol. 2, pp. 3-21, 1971.

[126] R. Mallett, "Meeting New Challenges for the U.S. Industry: Why Standards Matter.," in *Issues in Science and Technology*, 1998.

[127] G. Kolko, "Railroads and Regulation, 1877 - 1916." Princeton: Princeton University Press. 1965.

[128] M. E. Levine, "Regulatory Capture," *New Palgrave Dictionary of Economics and The Law*, vol. 3, pp. 267-271, 1998.

[129] S. G. Klauer, T. A. Dingus, V. L. Neale, J. D. Sudweeks, and R. D. J., "The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data," Virginia Tech Transportation Institute, Blacksburg, VA, W. Sponsored by National Highway Traffic Safety Administration, D.C., DOT HS 810 593, 2006 April.

[130] A. D. Andre and C. D. Wickens, "When users want what's not best for them," *Ergonomics in Design*, vol. 4, pp. 10-14, 1995.

[131] W. B. Arthur, *Increasing Returns and Path Dependence in the Economy*, University of Michigan Press, 1994.