Design and Testing of a Roadside Traffic Threat Alerting Mechanism

By

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Abstract

Every year, law enforcement officials, emergency personnel, and other workers stopped in traffic outside their vehicles are struck by inattentive drivers. Until now, most efforts to prevent these types of accidents have been geared toward making these at-risk parties more conspicuous to oncoming motorists. In contrast, this work proposes an alerting mechanism designed specifically to induce defensive behavior on the part of the at-risk officers (or other roadside personnel), once a hazardous situation has been detected. The immediate objective of this research was to produce an effective alarm prototype for a high noise, low-light operation environment such as a dimly lit highway shoulder. Based on fieldwork and background research, four such prototypes were engineered and evaluated for user response speed and subjective preference. Two of these alarm prototypes were auditory sirens and two were haptic vibrations, one placed at the waist, and one at the wrist. Haptic vibrations, which we hypothesized would be more salient in a loud and visually stimulating environment, proved to induce statistically significantly faster responses than the auditory alarms and were well received by the user community of State Police. The auditory sirens, however, were perceived as significantly more urgent than the haptic alarms and would be a beneficial addition to the haptic device to add redundancy to the system. Implemented in highway safety systems, the warning system developed through this work has the potential to help save lives.

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1 Introduction

1.1 Motivation

On October 19th, 2012, Nassau County highway patrol officer Joseph Olivieri exited his vehicle on the Long Island Expressway to investigate a crash and aid an injured person. Soon after, the 43-year-old father of two was struck and killed by another car. He had served the department for 14 years [1]. On December 29th, 2012, a similar collision occurred in northern New Jersey. Interstate Parkway Officer Christopher Finn was hit and knocked over a guard rail after stopping another vehicle on the highway [2]. Just days later on January 4, 2013, 27-year-old police officer Jamie Douglass was side-swiped during a traffic stop in Riley County, Kansas [3]. These kinds of on-duty accidents are all too common for law enforcement officers. In the United States, between 2000 and 2009, 120 law enforcement officers were struck and killed by vehicles while performing duties such as directing traffic, assisting motorists, or stopping on a highway shoulder [4].

As part of their job, police officers make stops in traffic or on highway shoulders, but the factors that contribute to hazardous traffic conditions are manifold. Today, automobiles have become fast and powerful machines, which are increasingly outfitted with automatic systems and distracting features that encourage driver multitasking and decrease alertness. With this kind of power, comes the responsibility to act with caution and patience while driving to ensure safety on the road. However, many drivers fall short. In 2009, there were an estimated 10.8 million crashes in the United States [5]. Poor highway engineering also endangers police officers and other personnel on the road. The Arizona Crown Victoria Police Interceptor (CVPI) Blue Ribbon Panel and the New York State Police recommend that officers position their highway stops parallel to the highway and sufficient distance from both violator vehicles and the edge of the highway [6]. Unfortunately, these types of stop locations are not always available. Highway engineers make exceptions to design standards and are often forced to reduce shoulder width or remove emergency breakdown lanes to help mediate high traffic volume [6]. Under these conditions, especially paired with obstructive weather conditions, rough terrain, or low visibility, there is little wiggle room for a stopped officer faced with an imminent collision. In such conditions, law enforcement officials simply cannot perform their duties without putting their own lives at serious risk.

Additionally, road construction workers, emergency medical personnel, and other first responders also face similar dangers on the job. In 2008, 29 of 114 firefighters killed on duty in the U.S. were killed in vehicle accidents. Between 1992 and 1997, at least 67 EMS providers perished in ground transportation related events [7].

1.2 Previous Work

A number of national agencies, including the American Association of State Highway and Transportation Officials and the National Safety Commission as well as international groups such as the International Association of Chiefs of Police, recognize these occupational hazards and work to establish practices to minimize them. In 2007, forty-three states had passed "Move Over" laws, which require oncoming traffic to clear the lane closest to a stopped officer [8]. However, the laws were not well-enforced and in a survey taken that year, 71 percent of Americans reported no knowledge of these laws [8]. To rectify this ignorance, the National Safety Commission, the National Sheriffs' Association and the National Association of Police Organizations have since spearheaded "Move Over, America" the first national educational campaign to stimulate knowledge of and conformance to the laws [8]. Another group, the Michigan Give 'em a Brake Safety Coalition supports the establishment of modified speed limits in work zones and in the past has installed "Where workers present 45" signs on the road. These signs mandate a speed limit of 45 mph when construction workers are present. They have also campaigned for their cause through bumper stickers and over radio [9].

Aside from policies, many devices and technologies also help protect officers and other workers on the road. Among the most popular are visual warnings and displays. Traffic cones, flares, signs, message boards, and reflective markings are all used to control and divert traffic in extraordinary conditions. Police uniforms often include retroreflective garments such as jackets and raincoats to help improve their conspicuity and the Federal Highway Administration requires that such garments comply with

American National Standards for High Visibility Safety Apparel and Headwear to ensure their tried and true visibility [10]. Brite Strike, a company started by two police officers, produces tactical illumination devices and has recently marketed LED gloves specifically designed for policemen directing traffic and on motorcycles [11]. Vehicles are also made more visible to traffic with visual cues. In terms of markings, studies have shown the benefits of retroreflective striping on police cruisers, that fluorescent colors are particularly effective during the day, and that contrasting colors are effective in making objects stand out from background noise [7]. With the use of LEDs, colors and light patterns can also be changed based on the amount of ambient light [6].

There are also haptic methods currently in place for protecting against vehicle accidents. Neel E. Wood, a retired Bridge Engineer, published a paper in 1994 presenting Sonic Nap Alert Patterns (SNAPs), indentations in the road surface that would produce a loud noise and vibrations in a vehicle passing over it. In his study, the use of SNAPs on the Pennsylvania Turnpike over five different projects produced a seventy percent reduction in drift off road accidents [12]. These types of haptic patterns, now more loosely referred to as "rumble strips" have also adapted to be raised features in plastic, ceramic, or asphalt materials, and have been used in various locations such as parking lots and between highway lanes. Rumble strips have also proved to be "more cost effective that many other safety features including guardrails, culvert-end treatments, and slope flattening [13] ."

Sirens and horns, today a quintessential feature of emergency vehicles, exemplify a third modality of warning signal on the road. While valuable when cutting through traffic and excellent at grabbing attention, these loud, conspicuous warnings can also be obstructive to police work and unnecessarily disturbing to neighboring communities. For this reason, sirens are typically only used brief periods of time, and rarely on a stationary vehicle.

However, even with all these precautions, drivers are fallible and crashes occur [14]. This thesis explores technology designed to actively warn officers of imminent danger. Unlike most other traffic safety devices, which are developed to target motorists, such a warning signal would be intended for law enforcement officers and other potential accident victims as a second line of defense if other passive signals fail.

1.3 Research Objectives

The goal of the work discussed in this thesis was to design and prototype an effective warning mechanism, which can be triggered when a dangerous vehicle is detected and which will effectively alert the individual at risk. In particular, it must be easy to use, easy to detect, and efficient in mobilizing the operator to take preventive action. It is also equally as important that the design is technically and fiscally feasible and users are willing and inclined to use this mechanism. The success of this work could potentially save hundreds of lives and fill a niche where no other alerting mechanism currently exists. For the users of this system, it could offer personalized security and peace of mind in an otherwise stressful environment.

The research outlined in this paper is motivated by a larger "Divert and Alert" project specifically designed for police officers stopped roadside. The "Divert and Alert" system will be positioned on top of police cruisers and will include an "Officer Alerting Mechanism", which is a physical alert paired with a machine vision system responsible for monitoring threat levels behind the cruiser [4].

Currently, machine vision systems are being developed to detect highway vehicle trajectories for applications such as traffic surveillance [15], [16]. These types of sensing systems can be trained to recognize anomalous trajectories through machine learning. To then trigger an officer alert mechanism, such a machine vision algorithm would likely interact with the police cruiser's machinery or other external hardware to produce a warning signal. In the near future, dedicated short-range communications (DSRC), further described in Chapter 6, will also open wireless communication channels between on-vehicle systems, infrastructure, and wireless devices.

Over the course of nine months, in collaboration with the Massachusetts State Police, a set of prototype alerts has been built that would integrate into the "Divert and Alert" project. As an evaluation of usability and efficacy, several studies were conducted examining the technical feasibility, alert detectability, and subjective response to these prototypes. The development process and results of experimentation with the proposed devices are detailed in the remainder of this paper.

1.4 Thesis Organization

This thesis is organized into the following six chapters:

- Chapter 1: Introduction – Introduces the motivation for this research and describes the high level goals of this work.
- Chapter 2: Background – Presents a literature review of materials relevant to this research topic.
- Chapter 3: Prototype Design and Implementation – Outlines the prototype requirements, design, and implementation details.
- Chapter 4: Usability Experiment – Describes the studies conducted to evaluate the efficacy of the proposed prototypes.
- Chapter 5: Experiment Results and Discussion – Covers the data gathered during experimentation with the prototypes and interprets these results.
- Chapter 6: Conclusion – Summarizes findings and suggests future work for this effort and forthcoming research

2 Background

This chapter begins by describing the user population and operation environment of the proposed alerting mechanism including a discussion of cognitive and psychophysiological theory concerning the interaction between humans and alerting mechanisms. The chapter then reviews various modalities of warning as well as warning staging and explores the effect of false alarms on alert effectiveness.

2.1 User Population and Roadside Environment

In general, police officers and other first responders are highly trained individuals who are skilled in fast decision-making, safety procedures, and emergency response. They are trained to be very familiar with their equipment and to be prepared for a wide range of situational circumstances. However, their work can be taxing on emotional and physical health. "Policing is a psychologically stressful work environment filled with danger, high demands, ambiguity in work encounters, human misery and exposure to death [17]." Furthermore, these occupations can come with undesirable shifts of duty, which cause fatigue and sleep deprivation. The Journal of American Medical Association reported that as many as 40% of nearly 5,000 police officers studied did not get enough sleep of had some sort of sleep disorder [18] . This is a serious risk factor on the job. It is a known fact that lack of sleep impacts cognitive performance and motor function [19] , and these resources are most vital in emergency situations.

The work environment for these individuals can also impair their ability to respond to threats. Traffic on the highway can be loud, visually demanding, and always changing. Weather conditions and terrain can reduce visibility of the surrounding area, making it harder to find escape routes, and temperature can cause discomfort and impaired tactile discrimination, especially in the cold [20]. All these factors must be accounted for in the development of a device for this environment.

2.2 Cognitive and Psychophysiological Theory

Characterizing the environment of a potential technology also requires understanding the cognitive state of potential users. Specifically, we are interested in the mental load on working officers, and how it will affect their ability to detect, recognize, and then respond to an alert. All of these cognitive tasks must be processed in a matter of seconds and any error in these three behaviors could cause a fatal delay.

2.2.1 Alarm Detection

Humans are generally capable of selectively attending to individual channels of stimuli [21]. For example, one can focus on completing a written assignment while listening to classical music, or one can follow a close range conversation while "tuning out" extraneous sounds in a noisy hall. Psychologists call this phenomenon the "cocktail party effect" [21]. It has been observed that accurate information pertaining to a single stimulus can be retained even in the presence of other competing stimuli. Early studies of attention employed a task called "shadowing" in which one message was presented to a participant in one ear, while another message was played in the other [21]. During the experiment participants were asked to repeat one of the messages verbatim. Using selective attention, this is not a difficult task. When prompted, humans can detect and follow a particular stimulus. However, similar studies have also concluded that remarkably little information from unattended channels is retained [21].

One way to work with this limitation is to draw upon cognitive resources in different channels of perception. Christopher Wickens' multiple resource theory proposes that cognitive resources are allocated to not one, but multiple processing structures which can function in tandem [22]. Four conclusions emerged from his work on information processing. First, perceptual and cognitive tasks use different processing resources than selection and execution [23]. Second, in perception, working memory, and action tasks, resources used for spatial activity and verbal/linguistic activity are distinct [23]. Third, auditory perception and visual perception use different resources [23]. And finally, that focal vision supports object recognition such as the perception of symbols whereas ambient vision is used for orientation and movement such as keeping in a lane on the highway [23].

These conclusions indicate that, theoretically, there are activities that one can perform concurrently without detracting from the other task. This could inform the design of systems for emergency workers, who will be attending to their work at the time any proposed device is in use. If an emergency alert can tap into unengaged cognitive resources, it will have the best chance of capturing attention.

2.2.2 Alarm Recognition

Alarm recognition may be difficult in environments that utilize multiple alarms. Increased numbers of alarms lead to a higher rate of recognition errors. In one Canadian hospital, a study demonstrated that only half of about fifty alarms were correctly identified by the clinical staff [24]. This suggests that high urgency alarms might be confused for lower priority alarms and thus, emergencies may go unattended.

We can also vary the content of the alarm to promote recognition. In one study [25], it was discovered that information which triggered higher skin conductance level and heart rate, both physiological changes associated with arousal, were more easily learned. For example, the word "vomit" was more easily remembered than lower arousal information such as the word "swim." This suggests that unique or particularly affecting stimuli are will be more easily recognized. It is also prudent to design alarms that are consistent with existing alarms because certain sounds may also have preexisting connotations for humans. For example, a siren would more quickly and intuitively be identified as a fire alarm than a pulsing sound, which might be associated with a heart rate monitor. Much work has been done to understand how manipulating different alarm features will affect their perception. Study in this area is further outlined in section 2.3.

2.2.3 Alarm Response

There are two types of mechanisms that can orient attention toward an alarm: exogenous mechanisms, prompted by abrupt events, and endogenous mechanisms, which cue alert signals with predictive events [26]. Exogenous mechanisms work by means of the orienting response. The concept is that when there are even slight changes in our environment we often respond to them by reflex like when a new person enters the room or when we hear an unusual sound in our environment. This is usually accompanied with a physiological response, such as pupil dilation, decreased frequency in respiration, or slowing of heart rate [25]. Behaviorally, one might physically orient one's eyes or body toward the stimulus. Alerts can take advantage of this natural instinct. For example, studies have shown that stimuli that increase in intensity may appear to be approaching and thus increase the orienting response. By contrast, stimuli that appear to recede cause less prolonged physiological changes [25]. Changes in stimulus significance and novelty can also trigger a stronger orienting response.

Concerning the use of endogenous mechanisms, it has been observed that priming, i.e. cuing to prepare the audience for an upcoming stimuli, enhances response to the stimuli. A series of studies by Posner and Snyder indicated that in the primed condition, participants reacted more quickly to stimuli than in a neutral condition (no priming). The misleading condition, which incorrectly primed the subject, would induce a similar or worse response time than the neutral condition based on the participant's expectation of predictor accuracy. But this applies specifically to the visual modality [21]. Posner also studied cuing in audition and touch [26]. His work confirmed that spatial cuing effects could be found in tactile and visual targets but not auditory. Spence and Driver further explored this discrepancy and found that in fact endogenous orienting in audition can be induced and will affect pitch and localization discrimination [26].

When designing an alerting system, one could capitalize on exogenous orientation by using an increasingly intensifying signal to indicate approaching dangerous vehicles. However, this requires a significant amount of time and may not be effective for situations in which a quick response is required. Endogenous mechanisms, by way of staging or multimodal signals could also speed up response time. These features will be detailed in the following sections.

2.3 Alert Modalities

This section explores the characteristics of three different modalities of warning: visual, auditory, and haptic. The benefits and drawbacks for each modality are summarized in Table 2-1 and detailed in the following sections.

2.3.1 Visual Alerts

The primary concern when designing a visual warning is that it should be noticed. "If a person does not see a warning then he or she will not receive (at least not directly) any information to assist in understanding the hazard and will be unable to make informed

Table 2-1: Summary of pros and cons for visual, auditory and haptic alerts

	Pros	Cons
Visual	▪ Can use language and images to describe hazard and preventive action required ▪ Easily distinguished from other alerts	▪ Difficult to notice if not directly in line of sight ▪ Visibility is affected by weather conditions ▪ Can be distracting to others
Auditory	▪ Can use language to describe hazard and preventive action required ▪ Easily noticed regardless of attention or activity ▪ Can easily convey a sense of urgency ▪ Resilient against weather conditions ▪ Can induce quick and orienting response	▪ Can be difficult to distinguish from other auditory alerts ▪ Can be distracting to others
Haptic	▪ Generally noticed regardless of attention or activity ▪ Resilient against weather, light, and noise conditions ▪ Not distracting to others ▪ Can induce quick and orienting response	▪ Can be difficult to distinguish from other haptic alerts

decisions [27] ." To improve visibility, warning designers employ techniques to increase the conspicuity of their warnings. For example, one could use large print, striking colors, and symbols and borders [27]. Comprehensibility is another important consideration in visual displays. Many road signs and other traffic control devices use text in place of, or in addition to symbols to better instruct drivers. But there is a tradeoff when using verbal messages in visual alerts. Text can be useful because we can use language to better indicate the reason for warning, the urgency of the warning, the appropriate action to be taken, or other useful information that might increase the accuracy of the response in situations where symbols may not be descriptive enough. However, in terms of response time, studies have shown that signs with symbols are responded to faster than signs with word messages [27]. But the benefits in both cases are contingent on the efficiency of their messages. Visual warnings must be simple and clear.

In the context of this project, any warning must be effective in all types of lighting and weather conditions. It is likely that a visual system would not be suitable for this requirement. On the road at night, traffic headlights can cause much light pollution and glare and at different times of the year fog, frost, dew and dirt can also significantly degrade visibility. In fact, in one study, "Rumar and Ost (1974) reported that, under unfavorable condition, dirt accumulation can reduce reflected light and contrast on small traffic signs up to 75% and 95% respectively [27]." We could avoid many of these visibility concerns by designing an on person mechanism that would be constantly in the officer's line of view but this type of device would be distracting and intrusive when not in use. Crash warning system guidelines published by the National Highway Traffic

Safety Administration specifically recommend visual warnings for "Continuous lower-priority information" and discourage their use for "Conveying time-critical information" which suggests that a visual alert would be highly inappropriate for our purpose [28]. For these reasons a visual display is not an effective choice for a highway alert mechanism.

2.3.2 Auditory Alerts

Auditory signals are effective as warnings because they act on a sense that is not easily ignored. "If a warning sound occurs, it will be detected automatically and routed through on a priority line to the brain [29]." Three different types of auditory sounds can be used as warning signals: abstract tones, auditory icons, and verbal messages [27], [30], [31]. An abstract tone is typically composed of a single or multiple tones, which can be pure or harmonically complex. These tones can be continuous, they can be pulsing, or they can otherwise vary temporally, but the distinct pattern of sound, whatever it may be, must be identifiable to humans and will require learning. It has been found that warnings which consist of single continuous tones or similar temporal patterns are easily confused [31].

Auditory icons are sounds that typically have pre-existing associations with the warning audience. They are typically composed of real world sounds that have a relationship with the circumstances they represent. For example, "the use of a doorbell to indicate the approach of a friendly entity [27], [32]" or "skidding tires to indicate that a vehicle crash is imminent [27], [30]." Because of this relationship, auditory icons are easier to learn and identify than abstract tones.

Finally, verbal auditory messages, like verbal visual messages, use language to signal warnings. They have similar benefits, costs, and challenges as well. Again, the comprehensibility of a verbal message is imperative for its effectiveness. Incoherent or long messages will delay reaction times and in a high noise environment. Verbal messages can also cause a language barrier when the user population speaks different languages. However, of the three types of auditory signals, if the appropriate language is used, verbal messages require the least learning, which could be suitable for an infrequent warning or one that appears in stressful situations that might cause listeners to forget the meaning of a more abstract alert [27].

Aside from the content of the sound, the physical characteristics of the signal can also be used to manipulate perception. Research has shown that "Fundamental frequency, harmonic series, amplitude envelope shape, delayed harmonics, and temporal and melodic parameters such as speed, rhythm, pitch range, and melodic structure all have clear and consistent effects on perceived urgency [33]." These characteristics also play an important part in the conspicuity and discriminability of the signal, two features that the National Highway Traffic Safety Administration has indicated are most important in the design of imminent collision warnings [28].

The human auditory system is much better at perceiving changes in sounds rather than absolute frequency or intensity [29]. This is important when making design decisions about frequency and amplitude in an auditory signal. Frequency refers to the number of wave cycles in a signal per unit time [27]. Pure tones are composed of a single sinusoidal wave while more complex signals can be composed of multiple sinusoids or other periodic waveforms. The human ear can detect frequencies between 20 and 20,000 hertz. While some frequencies are better heard than others, warnings sounds will generally be more resilient against environmental noise if they are composed of multiple sinusoidal tones [27]. Amplitude of a sound wave is synonymous with the volume of a signal. The louder the signal, the more easily it will be heard. However, high volume alarms can cause distraction to an unintended audience, annoyance, and for safety reasons. "A rule of thumb is that when sounds increase in level by approximately 10 dB (or dBA), their perceived loudness doubles (Casali, 1999) [27]." Auditory alarm guidelines suggest that a high urgency warning should be 10-30 decibels higher than the masked threshold, a measurement of listener hearing threshold based on frequency and decibel level [27], [28]. Through fieldwork, we have observed a 70-80 dB sound level on Massachusetts highways (Appendix A).

2.3.3 Haptic Alerts

Of the three modalities of warnings described in this thesis, haptic warnings have been the least studied. On the road, however, touch is an underutilized sensory channel and research has shown promising prospects for haptic alerts in comparison to visual and auditory warnings. In a study on collision avoidance, it was observed that reaction times to rear-end collision warnings was significantly shorter using tactile warnings than using visual warnings in a simulated driving environment and potentially also shorter than auditory warnings in real driving situations [34]. Rumble strips, tactile mechanisms mentioned in section 1.2, have now been installed all over the United States have drastically reduced drift-off-road accidents [12], [13], [27]. Although the roadside environment for officers is different than that for drivers in their cars, these studies suggest that tactile cues can be useful in circumstances that are perceptually taxing on the visual and auditory system.

Auditory or visual cues are often better indicators of orientation and location. They are both distal senses, capable of containing information about the distance of an event [35]. But if auditory and visual cues are impractical, haptic alerts can also be used to orient attention using directional spatial tactile cues. In a study, drivers were warned of front-end collisions through a haptic vibration on the stomach and rear-end collisions through a vibration on the back. "Participants responded 66 ms faster (and somewhat more accurately) following the presentation of a directionally appropriate tactile cue that following a spatially invalid cue [35]."

Haptic warnings are recommended in conjunction with warnings of other modalities to present redundant information [28], [36]. The combined message can create a sense of enhanced importance and enlarge the audience for which the warning will be effective, for example, persons with disabilities in perceiving one modality [27].

2.4 Staging and Multiple Warnings

When continuous information needs to be provided to the operators of a system, warning designers often choose to use multiple stages of warnings. In designing these alarms, it is important to be concerned with their frequency and discriminability from each other. It should be obvious to the user when each warning stage will be triggered, and it should be easy for the user to recognize each warning stage and act appropriately.

The benefit of staging warnings is increased awareness of potential danger. For example, as a potentially dangerous car approaches an officer roadside, warnings of increasing degree could be issued as the threat of a collision increases. By this implementation, we don't have to rely on a single threshold to determine whether or not the officer should be warned and the officer will have a chance to assess a threat before it potentially becomes more severe. On the other hand, having multiple warnings can increase annoyance or false alarms. Unnecessarily frequent alarms will also heighten "cry wolf behavior [37]," degrading the quality of operator response to the system. This effect is further explored in section 2.5.

2.5 False Alarms and Signal Detection Theory

False alarms are important to consider in alarm design because they can undermine the effectiveness of an alert if they cause the users to mistrust a positive signal. There are two ways that warning signals can produce false alarms: false negatives (missing alerts) and false positives (alerting when no danger exists). These two failure modes can be managed by using modeling frameworks that help appropriately calibrate the sensitivity of the system. To use these frameworks, we begin with one basic assumption: "The rational decision maker will always follow a perfect warning, but he or she will follow the recommendation of an imperfect warning only if the expected value (or utility) of ignoring the warning exceeds the expected value (or utility) of following it [27]."

Signal detection theory is a framework which represents the relationship between the decision making process and the accuracy of responses when mixed information is presented to an observer [38]. If the threshold for warning is too sensitive, false alarms are more likely, but misses can be avoided. If the threshold for warning it too high, false alarms are fewer but misses are more likely.

"Research in the psychological domain shows that people adjust their behavior according to the perceived false alarm rate [24]." Typically, when the false alarm incidence rate is too high, users tend to react to the alarm more slowly or not to respond at all. In one study, it was found that about 90% of subjects matched their alarm response rate to the reliability of the alarm [39]. But other work has indicated that the relationship between false alerts and operator behavior varies depending on context. For example, if users believe that the cost of a missed alarm is far more than the cost of ignoring a potentially false alarm, they may not change their behavior. In another experiment examining air traffic control alerts, false alarm rate did not appear to induce "cry wolf behavior," a decrease in response to an unreliable alarm [37].

In this project we are working with a high priority alert, which has a severe cost to misses. If an emergency situation is overlooked by the system, the consequences may be fatal to the user. However, if the system registers too many false positives, the alert will cause additional interruption in an already distracting environment. Thus, it is important that the algorithm that triggers the alarm is both conservative and accurate.

2.6 Chapter Summary

This chapter began by characterizing the operation environment and describing the physical and cognitive demands on the user population. It then went on to describe the various facets of cognitive and psychophysiological theory involving alerting mechanisms: alert detection, recognition, and response. The chapter then focused on aspects of alert design, comparing the effectiveness of visual, auditory, and haptic signals in a roadside environment and exploring the use of alert staging. The literature review concluded with a discussion of false alarms and signal detection theory, which can have a significant effect on the usability of the alert.

3 Prototype Design and Implementation

This chapter describes the design and implementation of auditory and haptic prototypes for an alerting mechanism. The chapter begins with a discussion of fieldwork conducted through a ride along with a State Trooper during routine traffic stops, followed by a summary of prototype requirements based on the conclusions of this research. The chapter concludes with a physical description of the design of the completed prototypes.

3.1 Ride Along

3.1.1 Objectives

To gain a better understanding of the operational environment, two of my colleagues and I conducted a ride along with a sergeant from the Massachusetts State Police. During the ride-along, we sat in the passenger seats of a police cruiser and observed the officer at work. Over the course of a few hours, we planned to make several roadside stops. At these stops, while the officer attended to the infraction and stopped party, we would exit the vehicle to collect data using digital cameras, video cameras, a decibel meter, and pen and paper.

There were several goals to achieve through this process. First, I was interested in understanding the cognitive requirements of the job by observing officer behavior. To this end, I conducted a short interview with the officer to observe and record the various actions and decisions the officer was required to make over the course of making a roadside stop. These findings are summarized in section 3.1.2.1. I was also interested in characterizing all other haptic, visual or auditory stimuli the officers experienced, with the purpose of gauging the sensory load of the environment. Decibel readings were taken around the vehicle on the shoulder of the road (section 3.2.1.2.) Finally, notes of equipment and uniforms were collected and are referenced in section 3.1.2.3. Observations from the ride along are included in Appendix A.

3.1.2 Findings

The ride along was conducted in late fall and after sunset, so the environment was cold and dark. We were given reflective jackets to wear as an additional safety measure. Over the course of the ride along, the officer stopped in four different roadside locations, both on the highway and in more suburban settings. When the officer detected a potentially dangerous vehicle on the road, it was essential that he did whatever was possible to maximize his safety and the safety of others before conducting the stop.

3.1.2.1 Timeline of a Roadside Stop

From observations during the ride-along and further discussion with the officer, I was able to gain an understanding of the timeline of a roadside stop. Figure 3-1 summarizes the sequence of events I observed each time the officer conducted a stop, and further details are described below.

As an officer begins to tail a dangerous vehicle, the targeted motorist will usually know that he or she is being followed by a police officer. However, the identity of the motorist is unknown to the officer. Inside the cruiser, each police officer has a computer interface, which matches license plate numbers with the registered owner of the vehicle, potentially the dangerous driver at hand. It is possible, of course, that the current driver is not the owner. The car may be borrowed, leased, or even recently stolen and not yet reported. Once the license plate has been run on the computer, the

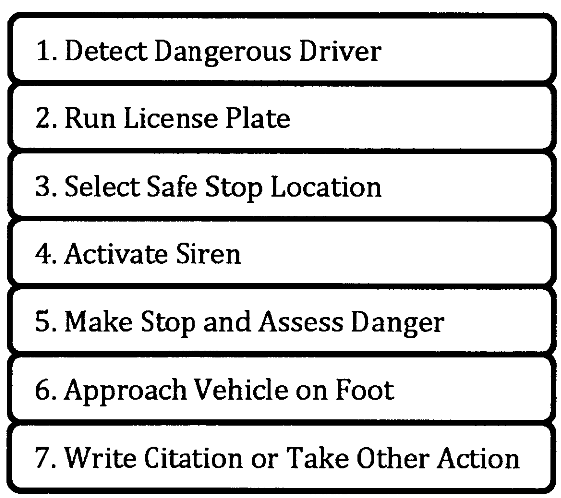


Figure 3-1: Sequence of actions when making a roadside stop. Police officers are trained to take these steps while driving, attending to oncoming traffic, and planning for emergency situations.

police officer will select a safe location to make the stop. At this point, the police siren may be turned on. Sometimes the target vehicle's driver will comply and other times they will not. For example, the driver may panic and stop his vehicle in the middle of the road or on the opposite side of the highway where no breakdown lanes exist. If the motorist is a criminal, he or she may become hostile or try to escape the situation. This latter possibility becomes more of a concern the longer the vehicle takes the to make the stop. As he is driving, the driver may be drawing a concealed weapon or searching for a personally advantageous location to make his stop where the officer's attention may be diverted.

After the officer exits his vehicle at the stop location, his or her attention is always divided between the stopped individual and oncoming traffic, both of which can pose serious threats to safety. Officers are trained to always be looking for escape routes in their environment, make their presence known to oncoming traffic, but also to conceal themselves from the targeted driver. They also may be required to go up to 100 yards away from their vehicle on foot. Based on an assessment of the situation, the officer chooses between wearing reflective gear or standard jackets, plans movement around the stopped vehicles and makes law enforcement decisions. Most of this behavior is taught through training and practiced by habit.

3.1.2.2 Noise in Roadside Environment

A decibel meter was used to measure decibel levels in various locations over the course of the ride along. Readings were also taken of other warning signals currently in use. The results are summarized in Table 3-2. Outside the vehicle in traffic, decibel readings varied between a maximum of 71 and 84 dB. Inside the vehicle, the readings reached up to 69 dB. The cruiser's built-in sirens and horns, gauged from about 30 feet away from the vehicle, reached decibel readings into the 90s.

All sirens are automatically turned off when the car is in park. The officer also carries an on-person radio and multiple other radios inside his vehicle.

Table 3-2: Summary of ride along decibel readings

Source	**Max Decibel Reading (dB)**
Inside Vehicle	69.0
Highway Shoulder	83.3
Suburban Neighborhood	71.0
Horn	85.5
Air Horn	90.5
Siren 1 (Wail)	92.9
Siren 2 (Yelp)	90.5
Siren 3 (Piercer)	90.7

3.1.2.3 Officer Uniform and Equipment

Uniforms consist of combat boots, a long sleeved shirt and slacks (or shorts in the summer) all on person items are carried on an external waist belt or cross-chest belt. Officers might wear multiple other layers of clothing e.g. a vest, jacket, or undershirt and their equipment can include a variety of equipment, such as radios, cell phones, and firearms, for various situations.

Figure 3-3: Massachusetts State Police winter uniform

3.2 Alerting Mechanism Prototype Requirements

Based on knowledge gathered from the ride along and the literature review, the requirements for the warning system were finalized.

At night on the highway, both the visual and auditory systems are especially fatiguing. With ambient noise decibel levels that can go well into the 70s and up to 80 dB, any auditory alert needs to be sufficiently loud to avoid being masked by other noises. So in terms of reqirements:,

1) For the best chance of detection, the alert must excite a sense that is not otherwise engaged or over stimulated in the operational environment.

2) The alert must produce the desired effect in a matter of seconds. Because there may only be seconds between the detection of a dangerous vehicle trajectory and the time the officer must move to a safe location, time is critical. For example, if a car is detected 100 yards away, a car travelling at 70 mph will travel that distance in 2.9 seconds. It is thus crucial that the speed of hazard detection and communication to the officer is maximized.

3) The alert signal must be succinct but descriptive enough to trigger both fast and accurate recognition.

4) The alert must be more urgent than and distinct from the other signals the officers may already have in use.

5) The alert must be effective at 100+ yards away from the police cruiser, since this is a typical distance officers travel from their car.

In addition to these technical requirements, we are also interested in usability issues. That is, the proposed alarm should be relatively easy for the target user community to transition into use. To this end:

6) The proposed implementation of the alert must be practically feasible in terms of cost and additional equipment. and

7) The alert must be safe, comfortable, and easy to use.

8) The target user group must be willing to use the device.

At this stage of the development process there were also some features that I did *not* implement in the prototypes. First, I did not use staging in the alert. Given the expected limitations of our machine vision system, it was likely that a dangerous vehicle trajectory would not be detected until just five to ten seconds before an accident occurs. This is insufficient time for multiple, staged alarms at this time. It may be possible for the system to make earlier detections, but this change would likely increase the occurrence of false alarms.

Unfortunately, this type of high priority alert could have a severe cost to false negatives. Taking precautionary action when no danger exists wastes time and energy and could become a major distraction from police work. Officers could begin to distrust this technology. The officers are also already required to respond to many other alerts and signals while on duty, so adding multiple warnings to communicate a single type of information could be unnecessary. It would be most effective to signal only when danger is imminent. Secondly, I will not be experimenting with multimodal warnings. For simplicity's sake, I have chosen to focus on individual modalities at this stage of the alert development process. Doing so will allow us the flexibility to experiment with variations within a single modality. Once the optimal physical characteristics of individual modalities are determined, future experimentation can explore the added dimension of multimodal alerts. This also allows me to focus on a comparison of the efficacy of the different modalities of alert apart from one another. Lastly, due to the need for omnipresent warnings because officers often have their visual attention directed towards the target vehicle, visual warnings were not included in this study.

Thus, I ultimately selected to explore the use of auditory and haptic stimuli as potential alert mechanism because of their practicality in a traffic operation scenario and based on the research outlined in Chapter 2.

3.3 Auditory Prototype Design

The Massachusetts State Police cruisers currently use three of ten preprogrammed siren tones on the SA314 series of Whelen box amplifier sirens, commonly referred to as "Wail", "Yelp", and "Piercer". From a practical standpoint, it would be a relatively effortless and low cost transition to activate one of the currently unused sirens. For this reason, we chose two of the remaining seven signal tones as prototypes for the officer alerting mechanism. The first, "Pulsed Airhorn" consists of a repeating two pulse tone, which repeats about every second. The second, "Woop", is a repeating single tone that increases in pitch over a period of about 250ms. These two particular signals, pictured in Figure 3-4, were selected for their distinguishability from the sirens currently in use and their perceived urgency. Other available signals had longer periods (lowering the perceived urgency), or were similar to "Piercer", "Yelp", and "Wail", the sirens already in use.

Based on the literature review, these proposed sirens also have several desirable characteristics consistent with our prototype requirements. First, both sirens have varying tonal characteristics, which are important for alert discrimination and

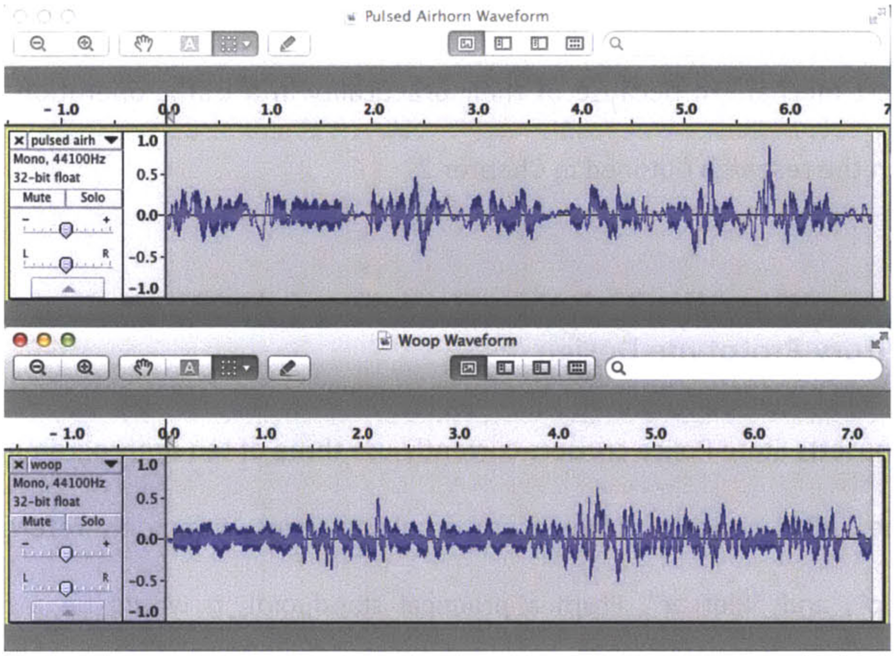


Figure 3-4: "Pulsed Airhorn" (top) and "Woop" (bottom) waveforms. The x axis represents time in seconds and the y axis represents digital volume. The digital volume ranges from -1 to 1 beyond which the signal will be distorted due to clipping.

recognition. The human auditory system is much better at perceiving changes in sounds than pure tones [29]. In terms of sound intensity, it is suggested that the signal have a 10 to 30 dB increase over the ambient environmental noise with a maximum of 90 dB [28]. Through our experience during the ride along, we know that highway sound can reach levels around 80db so, in practice, our proposed signal should be 90db. Like the signals currently in use, the Whelen box amplifier siren is able to reach this volume. At this sound level, these signals should be able to reach sufficiently long distances and still maintain the effectiveness we require.

3.4 Haptic Prototype Design

The haptic warning device designed for this system is a small on-person device that delivers a vibration signal when triggered. This trigger must be communicated wirelessly from a computer and work in all weather conditions. The device must also be comfortable to wear, and easy to use in addition to all the other devices the police already carry on their person. Unlike the auditory signals, the haptic warning device was engineered in the lab.

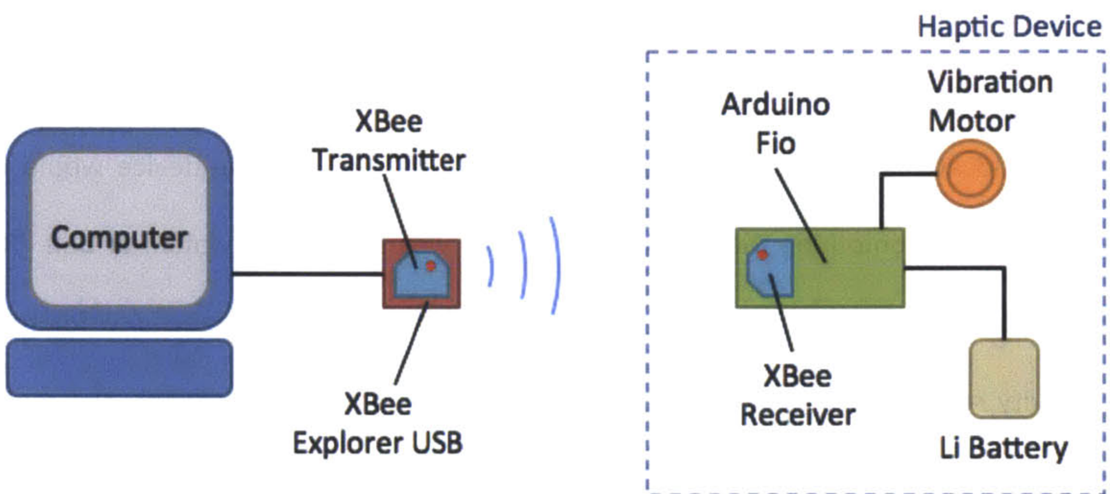


Figure 3-5: Haptic system diagram

To achieve wireless communication, I use XBee wireless radio frequency modules with both a 300-foot and one-mile range. When a hazard is detected by the machine vision system, a serial command is sent to the transmitting XBee from the computer, which will then transmit a trigger signal to the receiving XBee. The receiving XBee is connected to an Arduino Fio, a smaller version of the Arduino microcontroller specifically designed for wireless applications. The Fio powers an eccentric rotating mass motor to cause device vibration. These types of motors are similar in mechanics and intensity to those used in cellphones, game controllers and other vibrating devices.

To power the motor, the system requires a small circuit (not pictured in the image above). The Fio and motor are connected through a transistor, resistor, and diode combination further illustrated in Appendix B.

The device is encapsulated in a custom-made case using a 3D printer (Appendix C). The case features a small belt loop through which an elastic band can be threaded.

In experimentation, we were interested in using this device placed in two different locations: on the wrist and on the waist. Ideally, a haptic device would be integrated into something that the officer already wears such as a watch, or belt. The wrist and waist were thus chosen to mimic this kind of integration and also for their sensitivity relative to other locations on the body. In both these locations, the motor was placed in contact with the skin.

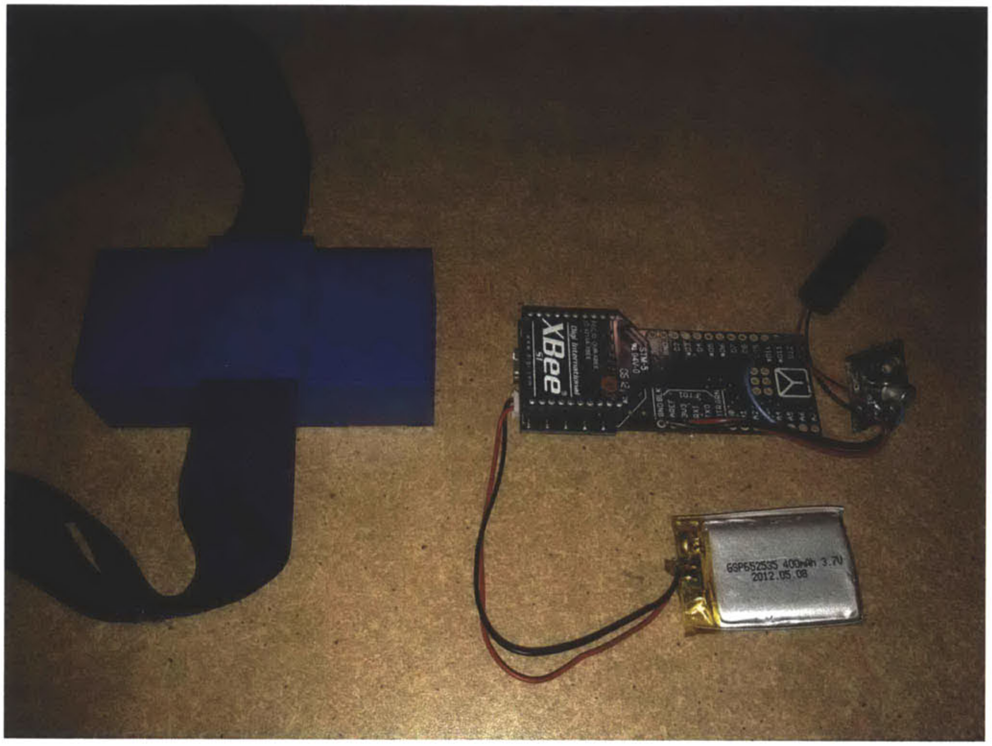


Figure 3-6: Haptic device hardware, consisting of Arduino Fio, battery, and vibration motor and fabricated case

3.5 Chapter Summary

This chapter began by detailing fieldwork, which in addition to literature review, dictated the requirements for alert prototypes. The following sections described the design of the prototypes. The auditory alerts were chosen from unused preprogrammed sirens already existing on current Massachusetts State Police cruisers. The haptic device, meant to be worn on the wrist or waist, was designed specifically for this application.

4 Usability Study

To assess the usability and effectiveness of the proposed prototypes, two studies were conducted: a human subjects experiment, and a consultation with members of the user community. This chapter describes the preparation and procedure for both of these studies.

4.1 Human Subjects Experiment

In this experiment, we were primarily interested in collecting detectability and subjective data from subject use of four prototypes: the haptic device located at the waist, the haptic device located at the wrist, the "Pulsed Airhorn" siren and the "Woop" siren.

4.1.1 Participants and Environment Set-Up

The study was conducted in an anechoic chamber located in the Research Laboratory of Electronics (RLE) at MIT. Forty participants were recruited from the MIT community and prescreened to exclude participants with any known hearing impairment. Each participant performed the experiment individually. Prior to experimentation, the subject was asked to complete the informed consent form included in Appendix D. After each session, each participant was asked to complete a short demographic survey included in Appendix E. All participants were compensated for their participation.

Several pieces of equipment were used inside the room at the time of experimentation. One laptop, dedicated solely to playing ambient highway noise collected during the ride along, was connected to an amplifier and a set of stereo speakers located on the right and left sides of the testing area. Another laptop, running the java application used to trigger the warning signals, was connected to a second set of speakers located in the front of the room. The transmitter for the haptic device was also connected to this second laptop.

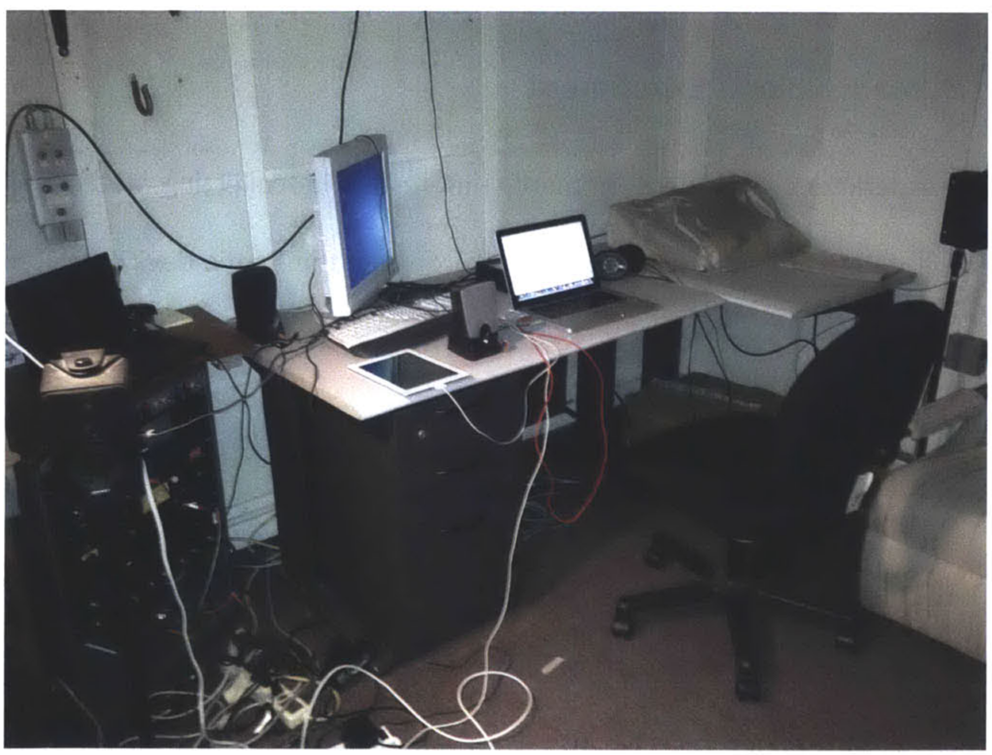


Figure 4-1: Testing set up

4.1.2 Procedure

All participants interacted with all four types of warning signals in a predetermined order. To correct for ordering effects, all twenty-four permutations of ordering were used in the first twenty-four subjects, and the remaining sixteen experiments were counterbalanced for the signals that were presented first and last. Forty random trigger times between thirty seconds and eight minutes were selected and a random permutation of these times were used across each type of alarm. Thus, the average trigger time for each alarm type across all experiments was identical. A table of experiment settings, indicating trigger times and alarm order is included in Appendix G.

The experiment was thus divided into four sessions, one for each alarm type. In sessions in which the participant was outfitted with a haptic warning device, he or she was instructed to press a key on the laptop placed in front of them when the warning mechanism vibrated. In the two other sessions, the participant performed the same action in response to an auditory signal (80-85 dB) played from the speaker located in the front of the room. To simulate the operation environment, recordings taken during the ride along of ambient highway noise were played over the right and left stereo speakers during each experimentation session. The decibel level of this playback varied between 70-77 dB. In our research and design phases, we concluded that highway noises may reach up to 80 dB and the optimal alarm decibel level might be 90 dB (a 10 dB increase over the max environment level). In our study, however, these levels were slightly reduced for safety reasons. Also during each session, the participant was asked to engage in a task to focus their attention. They were instructed to play any of several games on an iPad provided. The selection included the games, "Supermagical", "Angry Birds", "Unblock Me", "Candy Crush", "Icomania", "Jetpack", "Blitz", "Temple Run 2", and "CollapseBlast". Once the session was started, the alarm signal was triggered at one of 40 randomly selected times between 30 seconds and 8 minutes. Different permutations of this set of 40 trigger times were used for each of the conditions. The session would end 10 seconds after the alarm was triggered. Each session was preceded by a practice session in which the participant was given the opportunity to experience the stimulus but not respond to it. Following each session, each participant was asked to complete a questionnaire to gather subjective information about his or her interaction with the warning signals (Appendix F).

4.1.3 Data Collection

Two types of data were collected during this study. The first, mentioned before, was subjective information regarding each participant's experience with the four different types of warning signals. Second, during experimentation, a log file (Appendix H) was created containing information on alarm order, trigger times, response times (time between trigger and key press), subject number, and date.

4.2 Officer Assessment

Following the lab study, we set up informal interviews with members of the Massachusetts State Police to understand their perspectives on the proposed warning prototypes as well as to gather input for further iterations. The goal was to gain more knowledge about behavior on duty and the operation environment past what was observed during the ride along. The interview questions are included in Appendix I, and the findings from this dialogue are discussed in Chapter 5.

4.3 Chapter Summary

In this chapter, I described the methods used to evaluate the performance and response to the four prototypes introduced in chapter three. A user study simulating the operation environment was conducted to gather data on response times and subjective feedback. This was followed by a dialogue with members of the Massachusetts State Police force to gather further input from the expected user population.

5 Experiment Results and Discussion

This chapter presents the results of the usability studies described in the previous chapter. It begins by reporting findings from statistical analysis on the response time and subjective data gathered during the experiment and the moves into a broader discussion of the implications of this data. Finally, this chapter ends with a summary of findings from the interview conducted with the Massachusetts State Police officers.

5.1 Results from Aural vs. Haptic Experiment

There were several types of data logged during this experiment and the metrics for these measures are included in Appendix J. First, as a measure of performance, response time i.e. the time between the trigger of an alarm and the user's key press, was recorded. Of the forty participants, subjects 10, 17, 20, 27, 28, 30, 31, 35, 39, and 40 were missing response time data for at least one of the four conditions due to errors in the experimentation. For example, accurate readings could not be taken in cases where an alert malfunctioned, or the subject did not respond to the alert in the appropriate way. Measurements from these experiments were removed from the data set.

With the remaining data, I ran a one-way repeated measures ANOVA using response time as the dependent variable and the alarm type as the independent variable with 4 levels (See Chapter 5 for details on each level). There was a significant effect of alarm type on response time ($F(3,87) = 27.5$, $p < .0001$) indicating that some alarm types induced a significantly faster response than others.

A post hoc Tukey's pairwise comparison revealed the significant differences between "Woop" and Haptic on Wrist ($p < 0.001$), between "Woop" and Haptic on Waist ($p < 0.001$), between "Pulsed Airhorn" and Haptic on Wrist ($p < 0.001$), and between "Pulsed Airhorn" and Haptic on Waist ($p < 0.001$). A comparison between "Woop" and "Pulsed Airhorn" ($p > .05$) showed that response times to the two auditory alarms were not significantly different from one another. Similarly, a comparison between the Haptic on Wrist and Haptic on Waist ($p > .05$) also did not show a significant difference. These results indicate that the modality of warning had a very significant effect on the response time. More specifically, responses to haptic signals were around 0.7 seconds faster than responses to the auditory signals. Moreover, considering that two of each modality of signal was studied, the effect seems to be repeatable in experimentation. Figure 5.1 below illustrates the mean and standard error of the four conditions.

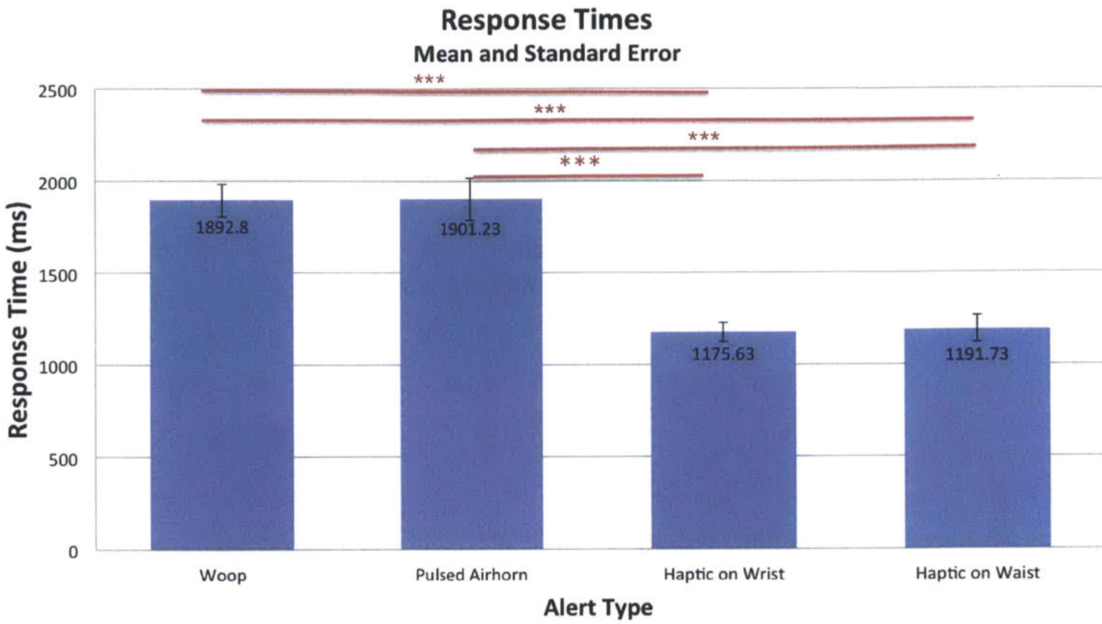


Figure 5-1: Mean and standard error of response times in each condition. Conditions that were significantly different are indicated in red.

In terms of subjective data, study participants were asked to rate several features of the haptic and auditory alerts using a five point Likert scale (Appendix J). Namely, subjects rated the intensity of the volume and pitch for the auditory alerts, the comfort of vibration, wear, and movement wearing the device for the haptic alerts, and detectability, signal urgency, warning appropriateness, and warning effectiveness for all four alerts. According to Wilcoxon matched pairs signed-rank test, there was no significant difference in volume ratings between the two auditory signals and no significant difference between the haptic alerts in comfort of vibration or comfort of wear. Volume was ranked on a scale of 1 through 5 from "Too Low" to "Too High". Comfort was ranked on a five point scale from "Very Uncomfortable" to "Very Comfortable." However, a Wilcoxon matched pairs signed-rank test showed that there was a significant effect of the type of auditory signal on ratings of pitch (W = 78, Z = 6.19, $p < 0.005$, r = 0.565). Pitch, like volume, was also rated from "Too Low" to "Too High." The mean and standard error of the pitch ratings are plotted in Figure 5-2.

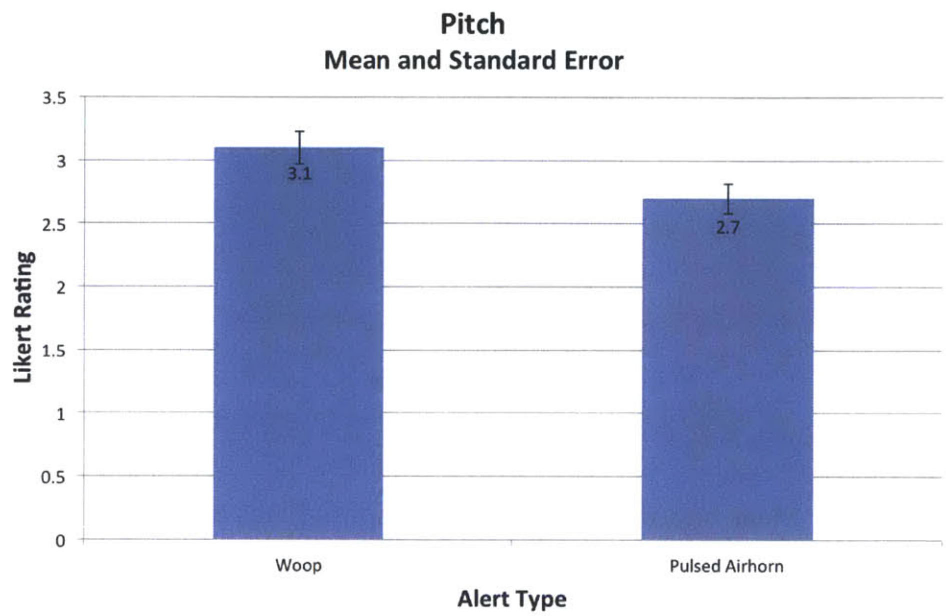


Figure 5-2: Mean and standard error of pitch ratings in each condition.

On average, subjects felt that the "Woop" siren was higher than pitch than the "Pulsed Airhorn" and tended to rate it closer to the "Too High" end of the scale.

For each of the four prototypes, subjects were also asked to rank detectability on a scale from a one, "Very Difficult to Detect" to five, "Very Easy to Detect." A Friedman test revealed no significant difference in ratings for detectability between the four conditions. However, a significant effect was found of alert type on ratings of urgency (X^2 (3) = 33.945, $p < 0.0001$). Urgency was rated from "Very Relaxed" to "Very Urgent." A post-hoc test using Dunn's Multiple Comparisons Test showed the significant differences between "Woop" and "Pulsed Airhorn" ($p < 0.01$), between "Woop" and Haptic on Wrist ($p < 0.001$), and between "Woop" and Haptic on Waist ($p < 0.001$). Looking at the urgency rating averages in Figure 5-3, we see that the "Woop" signal was rated as significantly more urgent that the other three. It is highly necessary for an emergency alert to communicate urgency. According to these results, subjects seem to perceive this signal characteristic the most in the "Woop" siren.

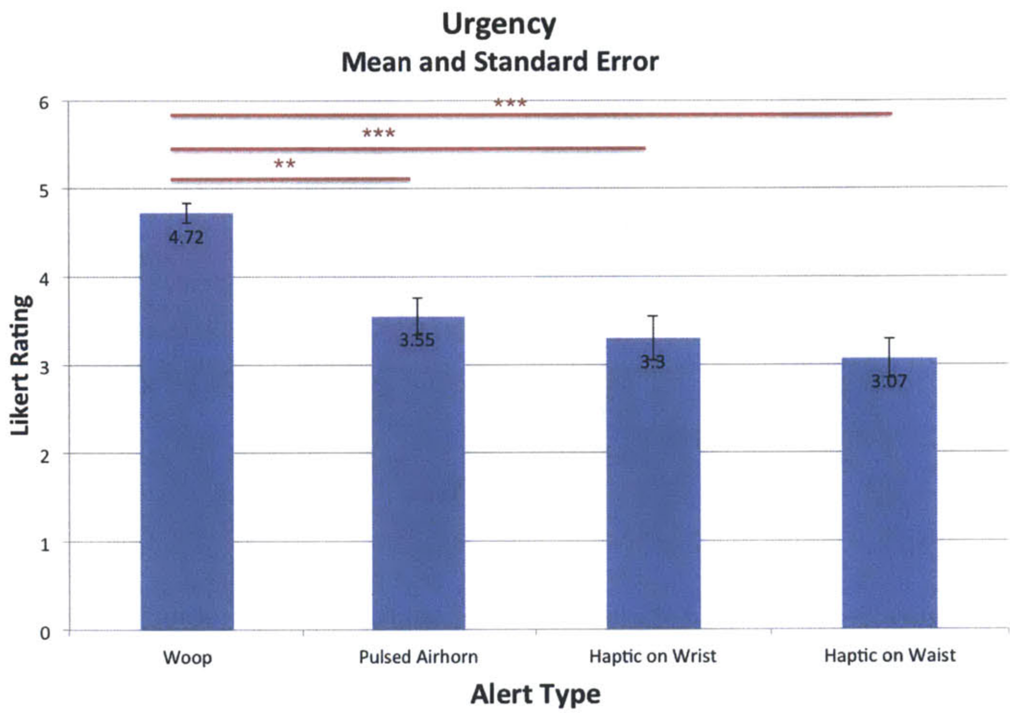


Figure 5-3: Mean and standard error of urgency in each condition, Conditions that were significantly different are indicated in red.

Similarly, "Woop" was also rated as significantly more appropriate in a hazardous situation than the haptic alerts ($X^2(3) = 29.23$, $p < 0.0001$). To gauge appropriateness, participants were prompted with the statement "To alert me of life threatening danger, this alert would be" and then asked to rank the alert from one, "Very Inappropriate" to five, "Very Appropriate." As pictured in Figure 5-4, there were significant differences between "Woop" and Haptic on Wrist ($p < 0.001$), and between "Woop" and Haptic on Waist ($p < 0.001$) in post hoc tests.

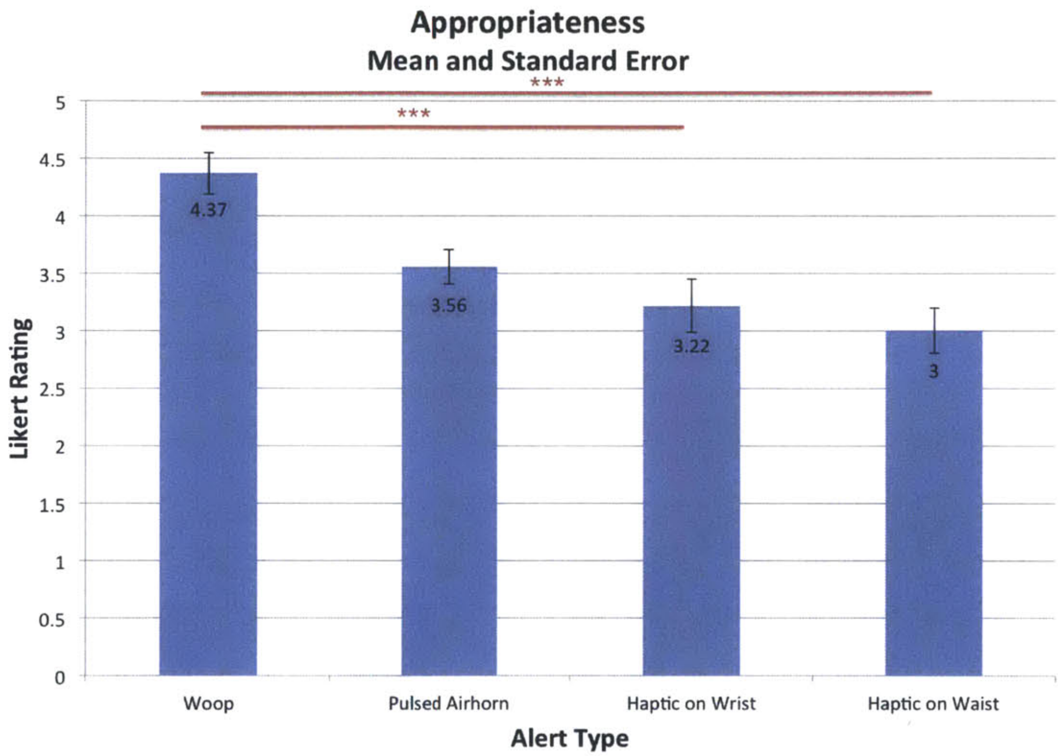


Figure 5-4: Mean and standard error of appropriateness rating in each condition. Conditions that were significantly different are indicated in red.

Finally, I found a significant effect of alert condition on the effectiveness rating ($X^2(3) = 21.514$, $p < 0.0001$) with significant differences between "Pulsed Airhorn" and Haptic on Waist ($p < 0.05$), between "Woop" and Haptic on Wrist ($p < 0.05$), and between "Woop" and Haptic on Waist ($p < 0.01$). Here again, participants were prompted with the statement "To alert me of life threatening danger, this alert would be" and then asked to rank the alert from one, "Very Ineffective" to five, "Very Effective." In these comparisons, the auditory sirens were rated higher than the haptic conditions as seen in Figure 5-5.

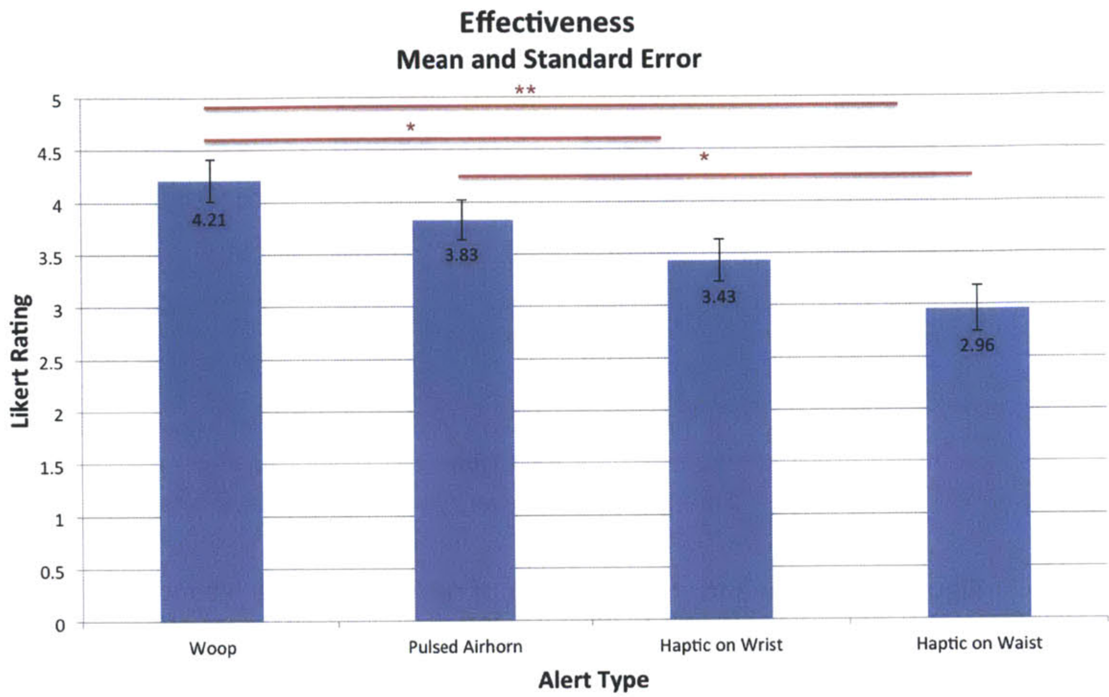


Figure 5-5: Mean and standard error of effectiveness rating in each condition. Conditions that were significantly different are indicated in red.

In addition to these Likert scale ratings, the subjective survey concluded with a request for rankings on all four prototypes based on preference ("1" being the most preferred and "4" being the least preferred). A Friedman test here revealed a significant effect (X^2 (3) = 11.427, $p < 0.01$). Dunn's multiple comparisons test only showed a significant difference between "Pulsed Airhorn" and Haptic on Waist ($p < 0.05$) in which "Pulsed Airhorn" was, on average, rated higher than the haptic signal located on the waist. Comparisons between other pairs of warnings were found to be insignificantly different. The results are summarized in Figure 5-6.

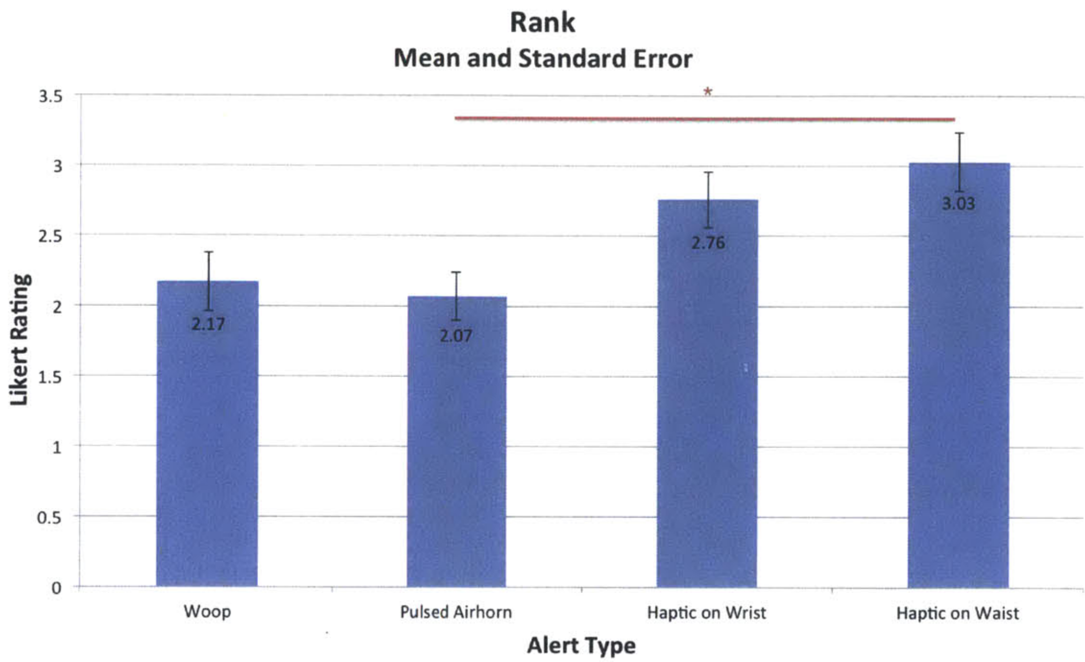


Figure 5-6: Mean and standard error of rank rating in each condition. Conditions that were significantly different are indicated in red.

5.1.1 Written Responses

In general, subjective written response varied in terms of whether subjects preferred the auditory or haptic signal. There was some general consensus, however, on various aspects of the individual prototypes.

For the haptic warning on waist, the vibration was generally perceived as detectible and comfortable although many participants likened the vibration to a cell phone vibration or that of other common devices. On the subjective survey, one participant stated, "Similarity to a phone makes it easy to ignore" and another responded with, "The vibration frequency wasn't "relaxed" but seemed along the same "force" as a hand held massager so doesn't exactly bring emergency to mind." Some even felt that the vibration was "ticklish." It seems that because of its similarity to sensations we have naturally learned to associate with other devices, the haptic alert loses its novelty and hence also its perceived urgency. Another common response to the haptic device was that it was at least mildly uncomfortable to wear and move around in. I feel that this feedback was generally expected and will be easy to improve in further revisions of the prototype. For example, the current device was designed with pointed corners, which could be rounded for better ergonomics and the hardware could be modified to be more efficient with space so it would be less bulky to wear. Eventually, the device can be integrated into a device or garment that is already used by the user, which would ideally maximize the comfort of wear.

Some responses to the haptic device on the wrist were similar to those with the haptic on the waist in terms of the quality of the vibration and wear. It was described as "a little unwieldy" and "Enough to signal/alert without stressful disturbance." In general however, many subjects compared the device in this location to a watch, a location that felt more natural than the waist. One common sentiment was that the vibration on the wrist was "much more comfortable than on the stomach." As with the haptic device on the waist, I believe that improvements in ergonomics could be made to enhance the user's experience when the device is attached to the wrist. One big advantage of incorporating vibration into a device, such as a watch, in this location, would be that the vibrating mechanism would be much more likely to maintain contact with the skin, and much less like to move when the user performs other activities.

In regards to the two auditory alarms, subjects tended to perceive the volume of both auditory alarms as "definitely audible" but also very close to the ambient noise. Although the sounds were controlled at 90db, about 10db higher than the ambient noise, it was common for subjects to observe that either auditory signal was "loud by itself but not when the background noise was on." In terms of pitch, the "Woop" siren contained higher frequencies than the "Pulsed Airhorn" signal, and accordingly was perceived as higher in pitch. In regards to the "Woop" siren, one subject commented, "Pitch was slightly on the high side but I feel that it stimulated an appropriate response" while many responded to the "Pulsed Airhorn" siren with comments such as, "Could be higher." For the remainder of the survey questions, i.e. detectability, urgency, appropriateness, and effectiveness, "Woop" was consistently rated as higher, and hence considered by participants as more appropriate in each of these categories than the "Pulsed Airhorn." In regards to the two sirens, comments included, "Catches my attention very well," and "Couldn't have done a better job." However, a common observation for both auditory signals was that they sounded similar to regular highway noises such as "truck horns" and "an actual siren." If this concern proves to be an issue in the field, it could be mitigated by engineering new and more unique sounds for the operation environment.

5.2 Officer Assessment Findings

Following the conclusion of the user study, I met with four members of the Massachusetts State Police force to demonstrate the prototypes and gather feedback that could help in further work on this project. All four individuals had background in the field and their experience ranged from 17 to 31 years on the force.

In response to the haptic signal, the officer wearing the device during the demonstration commented that the vibration "caught my attention right away" and all four agreed that the intensity was appropriately strong and different from that of a cell phone vibration. There were, however, varying opinions on the optimal location of wear. As a watch, some felt that it would be optimal in terms of maintaining the effectiveness of the device, but that most officers don't wear watches and that it would easily be forgotten. Another suggestion was to instead, integrate the vibration into the duty belt because "You are always going to put it on." However, there were concerns as to how easily the vibration would be felt through layers of clothing or when standing or sitting in different positions. The officers also came up with the idea of putting the device in a pocket and/or modifying uniforms to have holes where the motor could be placed in contact with the skin. Here, if the haptic device was separate from the clothing, it could be easily lost. If integrated into the clothing, there would be a need for multiple devices for each officer – one for each uniform. A fourth idea was to wear the device as a necklace and the other individuals seemed to agree that this was a viable option. When asked whether officers would be inclined to wear the device on a regular basis, the general consensus was positive. To maximize use, the equipment could be promoted during training and followed up with a policy mandating wear. In discussion of the haptic device, I also learned that in terms of battery life, the haptic device would need to run for up to 16 hours (the length of two typical shifts).

In response to the auditory alarm, all four officers agreed that they preferred the "Woop" over the "Pulsed Airhorn." The "Pulsed Airhorn" was "too similar to the air horn we already use." With the auditory alarm, there was also the concern that it would go off in a situation in which an officer would not want to bring attention to himself or herself (for example when watching a scene before going in). However, one of the officers acknowledged that the siren would not go off unless the emergency lights were on, based on the programming of the cruisers, and then the others seemed to agree that this was acceptable. The officers also agreed that in all cases, the warning should automatically be turned off after a ten second timeout.

Next, when asked if a multimodal warning incorporating the "Woop" signal and haptic device would be useful, the answer was a resounding yes. The auditory signal would "always be there" since it would be a part of the cruiser hardware itself and the haptic signal would be supplemental.

I also pitched a few other ideas that have been proposed during project meetings for future work. One idea was to sound the alarm through the on person radio handset using a resonant frequency that would also vibrate the hardware as well. In response, the officers unanimously agreed that such an alarm would interfere with communication and that the warning signal needed to be separate from the radio system. Another idea was to create a system that would provide continuous feedback depending on threat level, even in states of safety. This idea was also not well received. Finally, when asked if it would be beneficial to allow the officers to personalize their alert systems, for example allowing the users to choose his or her preference of siren tone, the officers felt that this would not be appropriate and that the alert should be kept standard.

Overall, the officers responded very positively to the prototypes presented during the meeting. The conclusion from this meeting is that the optimal emergency warning would be a combination of the haptic device and "Woop" siren. One of the individuals, serving as director of fleet operations, stated, "It's a great tool, I really do think," and concluded saying that, "if we can absorb that cost, it's a no-brainer."

5.3 Chapter Summary

In this chapter, I began by summarizing the findings from the user study, which indicated that the haptic alerts induced significantly quicker response times that the auditory alerts but that the "Woop" siren was received as significantly more urgent, effective, an appropriate than the other three. I then discuss the feedback gathered from a meeting with four officers from the Massachusetts State Police. The general response to the proposed prototypes was positive, and it was suggested that an optimal emergency warning would integrate both the haptic device and "Woop" siren.

6 Conclusion

6.1 Research Summary

In the field of emergency warning systems, there is limited work exploring the efficacy of auditory versus haptic warnings, especially in the type of operational scenarios discussed here. In my user study, I found not only that the haptic warnings were significantly quicker in stimulating a response, but also that the haptic alerts and auditory alerts were not significantly different within their modalities, indicating that these results are repeatable. In conversation with members of the user population, four officers of the Massachusetts State Police, the haptic and "Woop" alerts were well received from a practical standpoint, especially in conjunction as a multimodal alert, bolstering the prospect of their use in the field.

6.2 Future Technology

At this stage of the alert development process, we are primarily focused on prototyping, but there are some up and coming technologies that will be highly relevant to an industrial implementation of the type of alerting mechanism we are proposing.

6.2.1 Dedicated Short-Range Communications

Dedicated short-range communications (DSRC) is a technology that is currently being researched by the Intelligent Transportation Systems Joint Program Office at the U.S. Department of Transportation Research and Innovative Technology Administration [40]. DSRC is a short to medium range two-way wireless communications channel that allows interaction between a vehicle, wireless devices, and infrastructure such as roads. The primary motivation for this technology is for public safety applications and traffic management and as of 2003, has been implemented in electronic toll collection and electronic credentialing and monitoring of commercial vehicle operations. DSRC has several features that make it appropriate for an emergency application such as a designated bandwidth, fast network acquisition, privacy, and low latency. It also has the ability to give precedence to emergency communications and maintain high performance in high vehicle speed and poor weather conditions. This technology will be a valuable resource for implementation of any wirelessly triggered emergency alert operating in a highway environment.

6.2.2 Whelen Howler

Whelen Engineering Company, Inc. is now manufacturing the "Howler," a device that can be added on to an existing siren amplifier system that produces deep, low frequency tones you can feel. The primary motivation behind this technology is to add a layer of warning to the existing sirens which can better penetrate vehicles and be more effective in heavy traffic, intersections, or other high noise conditions [41].

Figure 6-1: Howler low frequency siren and speaker system [41].

These deep tones are synchronized with siren tones and can last from 8-60 seconds and it is recommended that operators wear hearing protection when the device is in use [41]. The price of outfitting a vehicle with a Whelen Howler comes out to several hundred dollars apiece, but the Howler is already being used in police fleets across the United States. The idea is that in noisy operation environments auditory sirens are too difficult to hear and easy to ignore, so the implementation of a siren that can also be felt will grab attention quickly. This concept of using a haptic signal where an auditory signal may be less salient is consistent with the work in this thesis. The device constructed in this research is designed to alert only the wearer. However, future work with technology like the Whelen Howler, can explore the benefits of broadcasting a haptic signal to many people at once.

6.3 Future Work

The work presented in this thesis is only the first design iteration for the development of an optimal alert mechanism for roadside safety. Given what I have learned and observed through this research, there are multiple interesting research and design questions that can be explored in subsequent work.

Referring back to the literature review and feedback from the officer interview, there were some features that I did not implement in the current prototypes that are worth investigating in future work. First, the existing prototypes could easily be integrated with each other or other modes of warning to create a multimodal alerting mechanism. With such a warning, it would be interesting to study whether a warning that uses two or more modalities can improve response time over the performance of either modality of warning individually. If time permits, a second modification might be to implement a staged warning for use in systems where such data is available. For example, a staged warning might issue alerts of increasing intensity based on the detection of danger at different thresholds of severity. A third modification would be to implement some sort of feedback mechanism with the alert that could help to train the triggering system to avoid false alarms. That is, each time the user experiences a false positive, he or she can press a button or provide some other kind of feedback to the system to indicate the error so that the system can use the corresponding data to learn more accurate detection.

In terms of modifying the existing prototypes presented in this paper, I would suggest several changes based on the feedback from the usability studies. For the auditory signals, the main concern was their similarity to existing sirens used by police officers as well as other emergency personnel. Subjects tended to prefer the siren-like sounds because, through experience, we associate emergencies with police and ambulance sirens. But, the overarching research question here is how to tap into people's naturally learned orienting response while maintaining the distinctiveness of the sound. One solution would be to engineer a new sound based on the desirable qualities outlined in chapter two, e.g. signal urgency and conspicuity. Although these sounds would not be available in the existing police cruiser hardware, the benefits of improving recognition may be worth the extra costs of implementation.

The haptic device could be best upgraded in two ways. First, it currently delivers a continuous vibration but could possibly benefit from a modification in intensity of the signal or in a change in vibration pattern. For example, an interesting research study might be to investigate the efficacy of varying frequencies of vibration or different pulse patterns in haptic devices. One could also study the extent to which users can distinguish different haptic alerts. Secondly, the current ergonomics and aesthetics of the device could be greatly improved. In the near future, small improvements such as rounded case corners and easier access to the battery charging port would certainly impact subjective response to the device, especially in terms of usability and comfort of wear. Subjective response to the haptic device is particularly important because the officers or other users of the device must feel inclined to wear it on a regular basis. As mentioned before, ideally, the haptic signal might be integrated into a device that the user already wears on a regular basis, such as a wristwatch or belt and based on the conversation with the state police, there is also work to be done in pinpointing the best method and location of wear.

Overall, this work is a solid stepping-stone for many different routes of future development on this project and in this field. Research on emergency alert design, particularly using haptic signaling, has much room for exploration and can be very impactful when implemented in consumer devices and systems.

Appendix A

Ride Along Notes

Decibel readings and observations collected during the ride along conducted November 2012.

Notes on Decibel Readings from Ride Along - 11/1/12

DECIBEL READINGS
(Max dB)

- Horn - 85.5
- Siren 1 (Wail) - 92.9
- Siren 2 (Yelp) - 90.5
- Siren 3 (Pierce) - 90.7
- Air Horn - 90.5

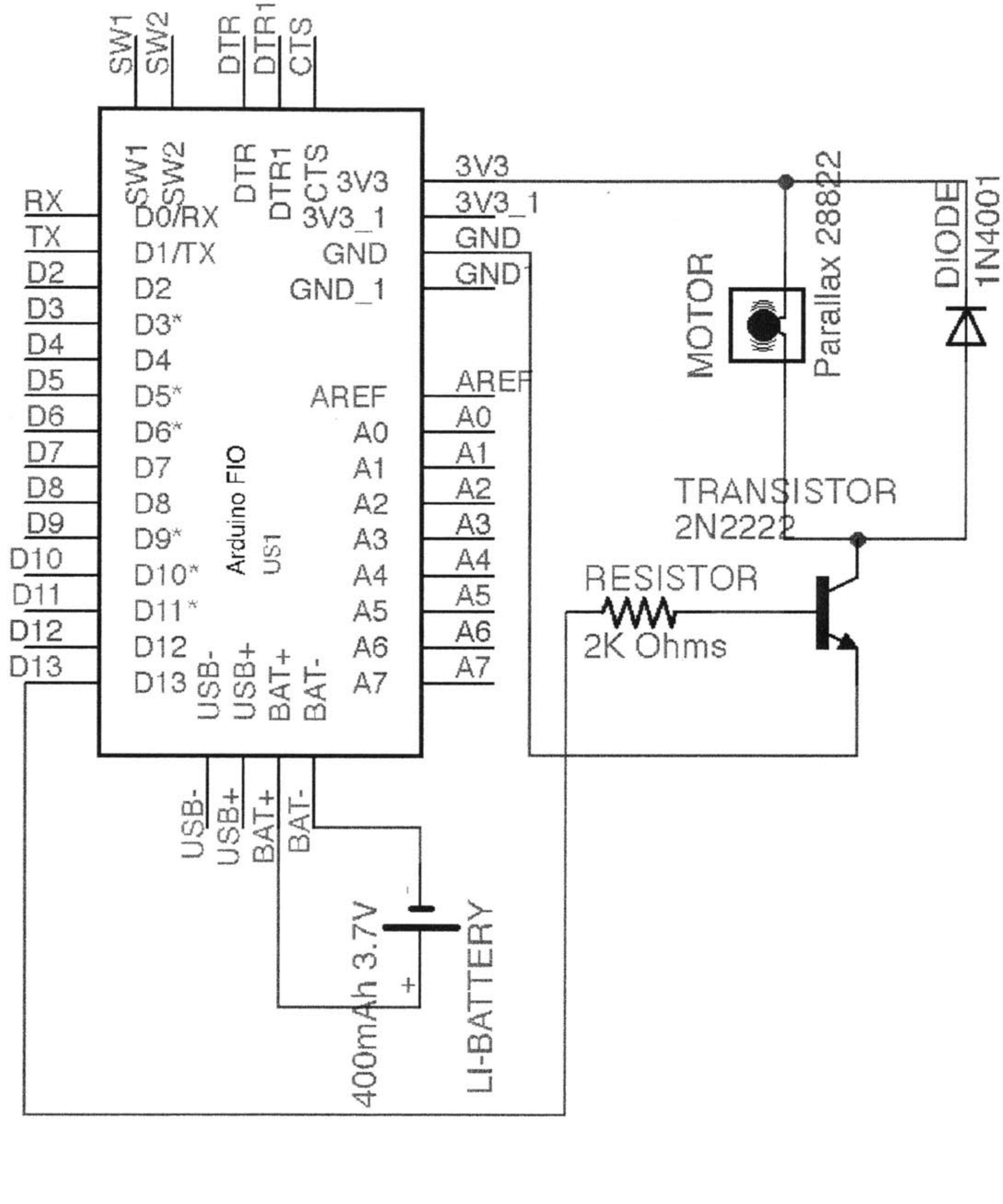
(dB)

- Inside vehicle - 59 to 69
- Highway shoulder, in front of vehicle - 78.8 (+ ~6 feet stop 1), 74 (+ ~12 feet stop 1), 82.9 (+ ~6 feet stop 2)
- Highway shoulder immediately to the right of vehicle (away from traffic) - 60 to 75 (stop 1), 73.6 (stop 2), 55.1 (stop 4)
- Highway shoulder, immediately behind vehicle - 83.3 (stop 4)
- Highway shoulder at guard rail- 75 to 80 (stop 1),
- Street side suburban neighborhood, front of vehicle - 71(stop 3)
- Street side suburban neighborhood - 59.6(stop 3)

Appendix B

Haptic Device Hardware Schematic

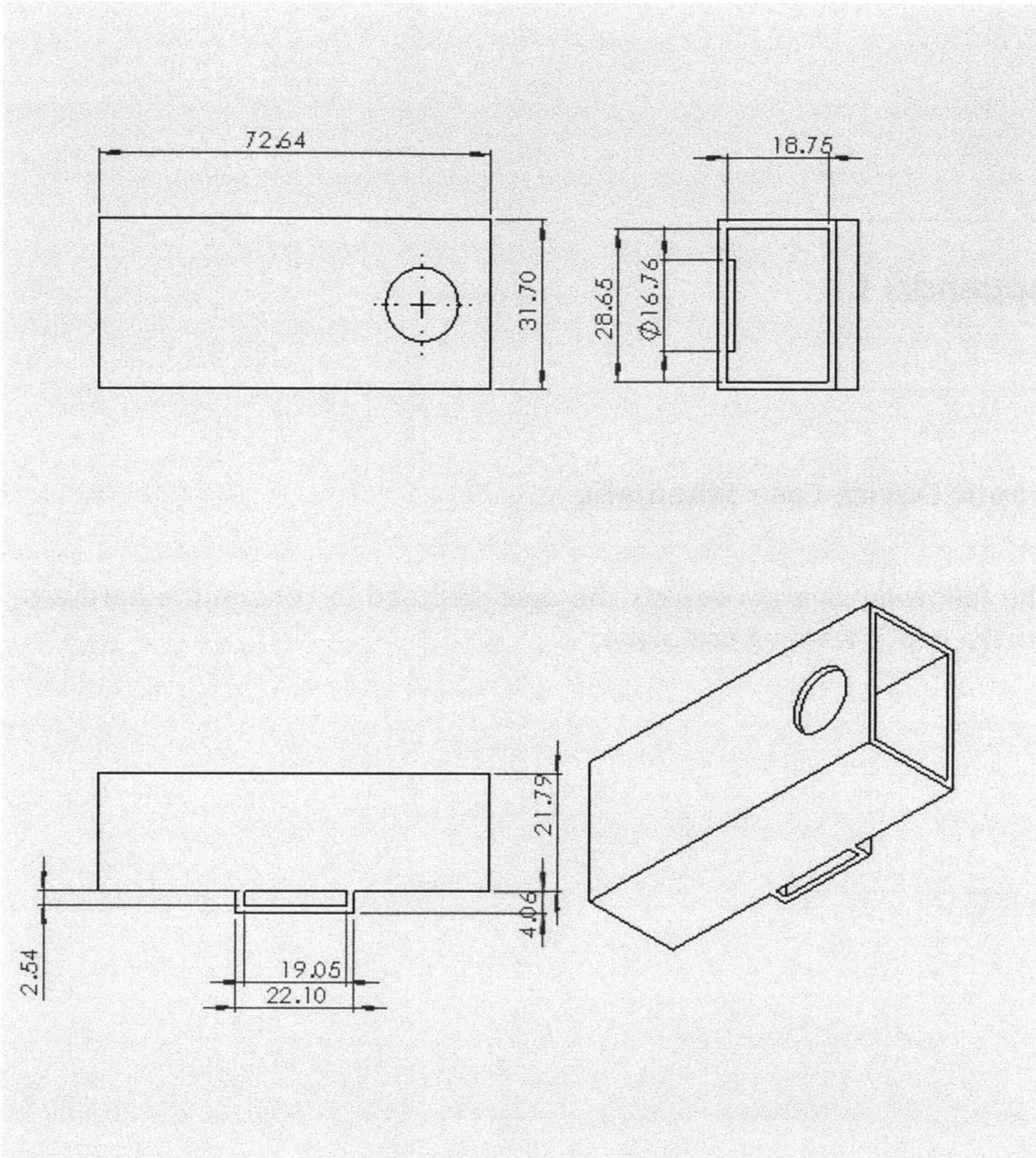
The following diagram depicts the hardware and circuitry used in the haptic warning prototype.


SW1
SW2
DTR
DTR1
CTS
3V3
3V3_1
GND
GND_1
RX
TX
D0/RX
D1/TX
D2
D3
D3*
D4
D5
D5*
D6
D6*
D7
D8
D9
D9*
D10
D10*
D11
D11*
D12
D13
AREF
A0
A1
A2
A3
A4
A5
A6
A7
Arduino FIO
US1
USB-
USB+
BAT+
BAT-
GND1
MOTOR
Parallax 28822
DIODE
1N4001
TRANSISTOR
2N2222
RESISTOR
2K Ohms
400mAh 3.7V
LI-BATTERY

Appendix C

Haptic Device Case Schematic

The following diagram depicts the case designed to contain the hardware for the haptic warning prototype.


72.64
18.75
31.70
28.65
Ø16.76
21.79
4.06
2.54
19.05
22.10

Appendix D

Consent to Participate

The following consent form was signed by each participant prior to participating in the human subjects study. COUHES approved on January 24, 2013. MIT IRB Protocol #: 1301005481.

CONSENT TO PARTICIPATE IN
NON-BIOMEDICAL RESEARCH

NIJ Divert and Alert: Operator Emergency Mechanism Study

You are asked to participate in a research study conducted by Pallavi Powale, a Master of Engineering Student from the Electrical Engineering and Computer Science Department at the Massachusetts Institute of Technology (M.I.T.). Results of this study will contribute to Pallavi's thesis work in developing an officer alerting mechanism. You were selected as a possible participant in this study because you are representative of the target population of this work. 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 purpose of the study is to evaluate and compare the effectiveness of haptic and auditory warnings in a high noise environment resembling that of a highway shoulder.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

There will be four approximately 12-15 minute sessions, two using haptic warning devices and two using auditory warning signals. During sessions with the haptic signal, you will be asked to wear a small device either on your wrist or on your waist and respond as quickly as possible using a clicker or keyboard button each time you feel a vibration. During sessions with the auditory signals, you will be asked to perform the same task in response to an auditory alert played over speakers. Over the course of each session, ambient highway recordings will be played.

Prior to each session, there will be a short practice session and following each session we ask that you complete a short survey. The entire experiment should take slightly over one hour to complete.

- **POTENTIAL RISKS AND DISCOMFORTS**

The testing environment will be loud, but noise levels will be controlled and kept under 90 db. No health risks are anticipated. If you feel any discomfort, you are always encouraged to communicate this to the experimenter.

- **POTENTIAL BENEFITS**

You may not benefit from this study directly. However, results of this study will aid in implementing an effective danger alerting mechanism for police officers and emergency personnel at work. It has the potential to save hundred of lives.

- **PAYMENT FOR PARTICIPATION**

You will be given $15 dollars per hour in cash to participate in this study. This will be paid upon completion of your debrief. Should you elect to withdraw in the middle of the study, you will be compensated for the hours you spent in the study.

- **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.

Participants will be deidentified using subject numbers and data will be stored on laboratory computers secured by physical door locks and computer password protection.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact Pallavi Powale at email: ppowale@mit.edu or phone: (858) 201-9647. Alternatively, you may contact Professor Seth Teller at email: teller@csail.mit.edu or phone: (617) 230-8756.

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

If you feel you have suffered an injury, which may include emotional trauma, as a result of participating in this study, please contact the person in charge of the study as soon as possible.

In the event you suffer such an injury, M.I.T. may provide itself, or arrange for the provision of, emergency transport or medical treatment, including emergency treatment and follow-up care, as needed, or reimbursement for such medical services. M.I.T. does not provide any other form of compensation for injury. In any case, neither the offer to provide medical assistance, nor the actual provision of medical services shall be considered an admission of fault or acceptance of liability. Questions regarding this policy may be directed to MIT's Insurance Office, (617) 253-2823. Your insurance carrier may be billed for the cost of emergency transport or medical treatment, if such services are determined not to be directly related to your participation in this study.

- **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 E25-143B, 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

Demographic Form

The following form was completed by all participants at the beginning of the human subjects experiment.

Subject #_____

DEMOGRAPHIC SURVEY

1) Gender:
- o Male
- o Female

2) Age:

3) Please indicate your occupation (if student, indicate your year and degree)?

4) Do you have any hearing impairment? If so, please explain?

5) Are you right-handed or left-handed?

6) What is your experience playing the iPad game you played during the experiment?

Thank you for your participation!

Appendix F

Post Experiment Questionnaire

The following questionnaire was given to participants during the human subjects experiment to collect subjective data.

Edit this form

Post Experiment Survey

Subject

Haptic Device on Waist

Please check the circle that best represents your experience with each type of signal. Please provide additional details on your rating in the comments section below each question.

Comfort of Vibration

	1	2	3	4	5	
Very Uncomfortable	○	○	○	○	○	Very Comfortable

Comments

Comfort of Wear

	1	2	3	4	5	
Very Uncomfortable	○	○	○	○	○	Very Comfortable

Comments

Movement while Wearing Device

	1	2	3	4	5	
Very Difficult	○	○	○	○	○	Very Easy

Comments

Detctability of Alert

	1	2	3	4	5	
Very Difficult to Detect	○	○	○	○	○	Very Easy to Detect

Comments

Signal Urgency

	1	2	3	4	5	
Very Relaxed	○	○	○	○	○	Very Urgent

Comments

Appropriateness in Hazardous Situation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Inappropriate	○	○	○	○	○	Very Appropriate

Comments

Effectiveness in Hazardous Situation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Ineffective	○	○	○	○	○	Very Effective

Comments

How would you change the system to have it better alert you to a life threatening danger?

In general how would you changes this alert to get your attention in any situation?

Please express any additional comments you'd like to share

Continue »

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Edit this form

Post Experiment Survey

Haptic Device on Wrist

Please check the circle that best represents your experience with each type of signal.
Please provide additional details on your rating in the comments section below each question.

Comfort of Vibration

	1	2	3	4	5	
Very Uncomfortable	○	○	○	○	○	Very Comfortable

Comments

Comfort of Wear

	1	2	3	4	5	
Very Uncomfortable	○	○	○	○	○	Very Comfortable

Comments

Movement While Wearing Device

	1	2	3	4	5	
Very Difficult	○	○	○	○	○	Very Easy

Comments

Detectability of Alert

	1	2	3	4	5	
Very Difficult to Detect	○	○	○	○	○	Very Easy to Detect

Comments

Signal Urgency

	1	2	3	4	5	
Very Relaxed	○	○	○	○	○	Very Urgent

Comments

Appropriateness in Hazardous Situation
To alert me of life threatening danger , this alert would be

	1	2	3	4	5	
Very Inappropriate	○	○	○	○	○	Very Appropriate

Comments

Effectiveness in a Hazardous SItuation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Ineffective	○	○	○	○	○	Very Effective

Comments

How would you change the system to have it better alert you to a life threatening situation?

In general how would ou change the alert to get your attention in any situation?

Please express any additional comments that you would like to share

« Back   Continue »

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Edit this form

Post Experiment Survey

Auditory Signal: "Pulsed Airhorn"

Please check the circle that best represents your experience with each type of signal.
Please provide additional details on your rating in the comments section below each question.

Volume

	1	2	3	4	5	
Too Quiet	○	○	○	○	○	Too Loud

Comments

Pitch

	1	2	3	4	5	
Too Low	○	○	○	○	○	Too High

Comments

Detectability

	1	2	3	4	5	
Very Difficult to Detect	○	○	○	○	○	Very Easy to Detect

Comments

Signal Urgency

	1	2	3	4	5	
Very Relaxed	○	○	○	○	○	Very Urgent

Comments

Appropriateness in Hazardous Situation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Inappropriate	○	○	○	○	○	Very Appropriate

Comments

Effectiveness in Hazardous Situation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Ineffective	○	○	○	○	○	Very Effective

Comments

How would you change the system to have it better alert you to a life threatening situation?

In general how would you change the alert to get your attention in any situation?

Please express any additional comments you would like the share

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Edit this form

Post Experiment Survey

Auditory Signal: "Woop"

Please check the circle that best represents your experience with each type of signal.
Please provide additional details on your rating in the comments section below each question.

Volume

	1	2	3	4	5	
Too Quiet	○	○	○	○	○	Too Loud

Comments

Pitch

	1	2	3	4	5	
Too Low	○	○	○	○	○	Too High

Comments

Detectability

	1	2	3	4	5	
Very Difficult to Detect	○	○	○	○	○	Very Easy to Detect

Comments

Signal Urgency

	1	2	3	4	5	
Very Relaxed	○	○	○	○	○	Very Urgent

Comments

Appropriateness in Hazardous Situation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Inappropriate	○	○	○	○	○	Very Appropriate

Comments

Effectiveness in Hazardous Situation
To alert me of life threatening danger, this alert would be

	1	2	3	4	5	
Very Ineffective	○	○	○	○	○	Very Effective

Comments

How would you change the system to have it better alert you to a life threatening situation?

How would you change this alert to get your attention in any situation?

Please express any additional comments you would like to share

« Back | Continue »

Edit this form

Post Experiment Survey

Rank the signals in order of preference (highest to lowest)

	1	2	3	4
Haptic on waist	○	○	○	○
Haptic on wrist	○	○	○	○
"Pulsed Airhorn"	○	○	○	○
"Woop"	○	○	○	○

Comments

« Back | Submit

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Appendix G

Experiment Settings

The following table indicated the order in and trigger times at which the four alarm types were presented to subjects during the user study.

Alarm Types:
1 = "Woop" siren
2 = "Pulsed Airhorn" siren
3 = Haptic device on wrist
4 = Haptic device on waist

	Session order				Trigger time (seconds) by alarm type:			
subject	first	second	third	fourth	1	2	3	4
1	1	2	3	4	175	32	294	36
2	1	2	4	3	380	33	475	342
3	1	3	4	2	65	211	234	114
4	2	1	3	4	289	322	300	197
5	2	3	1	4	234	161	186	297
6	4	3	2	1	217	98	475	184
7	4	1	3	2	170	225	338	261
8	3	4	1	2	71	368	426	100
9	4	3	2	1	217	36	184	322
10	3	1	2	4	170	114	211	294
11	2	4	1	3	197	65	322	380
12	2	4	3	1	297	300	33	98
13	3	2	4	1	170	368	186	65
14	3	1	4	2	36	217	114	225
15	4	1	3	2	98	426	289	161
16	3	4	1	2	184	342	217	300
17	1	2	3	4	360	71	225	368
18	2	4	3	1	475	197	65	170
19	1	3	2	4	322	100	300	33
20	1	4	2	3	211	217	217	234
21	1	4	3	2	32	170	98	170
22	2	1	4	3	33	360	197	338
23	2	3	4	1	300	294	261	368
24	3	2	1	4	475	289	342	120
25	3	4	2	1	342	380	175	186
26	4	1	2	3	186	120	170	289
27	4	2	1	3	426	338	380	175
28	4	2	3	1	368	261	32	217
29	4	3	1	2	261	475	120	360
30	1	3	4	2	186	297	368	217
31	2	1	3	4	300	175	186	170
32	2	3	4	1	338	234	297	300

33	3	1	2	4	186	186	100	186	
34	4	1	2	3	225	170	368	71	
35	3	2	4	1	368	300	360	475	
36	1	4	3	2	120	170	170	426	
37	2	4	1	3	294	475	161	211	
38	1	2	3	4	114	186	71	32	
39	3	2	1	4	100	184	170	475	
40	4	2	1	3	161	186	36	186	
					228.825	228.825	228.825	228.825	<- Averages

Appendix H

Data Log Example

An example of the information that was logged for each participant as the experiment was in progress.

Alarm Types:

1 = "Woop" siren
2 = "Pulsed Airhorn" siren
3 = Haptic device on wrist
4 = Haptic device on waist

Data logged in CSV file:

subject number 0	date: 3/18/13	
Alarm Type	Triggered At(ms)	Reaction Time(ms)
2	322000	1756
1	289000	2512
3	300000	1149
4	197000	1023

Appendix I

Officer Assessment Interview

Topics of discussion used during the informal officer assessment.

1. Introductions
2. Describe NIJ Project
3. Describe Thesis Work
4. Demo signals

QUESTIONS

- What kinds of stop locations do you encounter? I witnessed a stop on the highway and in a neighborhood. Is there any other situation we should be aware of? What about crash sites? Other special circumstances?
- What are some instances when this system would have been useful to you? What would have been useful to you? What features would you have liked to have?
- What kind of training do you receive on the use of warning signals?
- How aware are you of your surroundings?
- Is it better to have an alert that everyone in the vicinity can hear, or is it better if it's a personal alarm?
    - How do/will others react? Motorists..the person pulled over..
    - What would be the consequences in the case of a false alarm?
- I understand that you go through extensive training, but even then, do you feel that these signals are too similar to the ones you already use?
- Would you be willing to wear a extra device? Or if we could incorporate the vibration into something that you already use, what would be the best option?
- How often/ how sensitive would you want the signal to be? How early would you want it to go off, i.e. how much time would you need to move to a safe location?
- We're planning on making this alarm a very high priority alarm. In practice, would this be the case?
- Other ideas are to have the auditory signal come from the on person radio, or to use a multimodal auditory-haptic alarm. Thoughts?

Appendix J

Experiment Metrics

A report of the mean, median, standard deviation, minimum, and maximum for each of the metrics collected during the experiment.

Demographic Metrics

23 Female

17 Male

Performance Metrics

Metric	Condition	N	Mean	Median	Std. Dev.	Min	Max
Response Time	"Woop"	30	1892.8	1775	478.53	1174	2912
	"Pulsed Airhorn"	30	1901.23	1698.5	628.12	1264	4260
	Haptic on Wrist	30	1175.63	1102	286.71	852	2201
	Haptic on Waist	30	1191.73	1139	400.69	674	3001

Subjective Metrics

Metric	Condition	N	Mean	Median	Std. Dev.	Min	Max
Volume	"Woop"	30	3.13	3	0.63	2	4
	"Pulsed Airhorn"	30	2.97	3	0.67	2	4
Pitch	"Woop"	30	3.1	3	0.71	2	5
	"Pulsed Airhorn"	30	2.7	3	0.65	1	4
Comfort of Vibration	Haptic on Wrist	30	4.1	4	0.92	2	5
	Haptic on Waist	30	3.73	4	1.02	1	5
Comfort of Wear	Haptic on Wrist	30	3.73	4	0.94	2	5
	Haptic on Waist	30	3.4	3	1.07	1	5
Movement	Haptic on Wrist	28	3.79	4	1.07	2	5
	Haptic on Waist	28	3.71	4	1.12	2	5
Detectability	"Woop"	28	4.18	5	0.98	2	5
	"Pulsed Airhorn"	28	4.07	4	0.90	2	5
	Haptic on Wrist	28	4.32	4.5	0.82	2	5
	Haptic on Waist	28	4.29	4	0.76	3	5
Signal Urgency	"Woop"	29	4.72	5	0.59	3	5
	"Pulsed Airhorn"	29	3.55	4	1.12	2	5
	Haptic on Wrist	29	3.28	4	1.36	1	5
	Haptic on Waist	29	3.07	3	1.19	1	5
Appropriateness	"Woop"	27	4.37	5	0.93	2	5
	"Pulsed Airhorn"	27	3.56	4	0.80	2	5
	Haptic on Wrist	27	3.22	3	1.19	1	5
	Haptic on Waist	27	3.00	3	1.04	1	5
Effectiveness	"Woop"	28	4.21	5	1.07	2	5
	"Pulsed Airhorn"	28	3.83	4	1.02	1	5
	Haptic on Wrist	28	3.43	4	1.07	1	5
	Haptic on Waist	28	2.97	3	1.14	1	5
Rank	"Woop"	29	2.17	2	1.14	1	4
	"Pulsed Airhorn"	29	2.07	2	0.92	1	4
	Haptic on Wrist	29	2.76	3	1.06	1	4
	Haptic on Waist	29	3.03	3	1.12	1	4

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