The Use of Auditory Cues to Provide Dynamic Alerts to Drivers

By

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Submitted to the Department of Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Electrical Engineering and Computer Science at the Massachusetts Institute of Technology September 10, 2001

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ABSTRACT

Driving is a highly complex and largely visual task. Several papers have explored the possibility of using auditory cues for alerts, particularly in collision avoidance systems. These suggest that auditory alerts can improve the response to a dangerous situation. The auditory alerts used to-date however, have been non-spatial. This study seeks to investigate whether a spatialized alert can improve a driver’s response to a potential front–rear collision resulting in safer driving. Two different types of spatial alerts are tested versus a recommended non–spatial auditory alert. The first spatial alert is simple a spatialized version of the non–spatial alert. The second spatial alert is a new type of auditory alert, which provides earlier notice of an impending collision, but less intrusively. Each of these is tested with and without a simple heads–up visual alert. Experimental verification was performed by presenting driving simulation scenarios to several subjects using the different alerts and analyzing their response and behavior to each.

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1 Introduction

1.1 Motivation

Driving a car can be split into three sub-tasks: receiving input on the location and surrounding environment of the car, processing the input data to decide what to do next, and converting this decision into movement controlling the car. The three are intricately bound into a single feedback loop that binds the behavior of the car together with that of its driver. The first of these tasks is almost completely visual. The main inputs to the driver are the data presented via the dashboard and the visual scene through the windshield and via mirrors. This system is fairly successful, but over 3 million accidents still occur annually with over 40,000 lives lost to vehicular collisions every year.

There is a long line of research seeking ways to reduce this ghastly figure. One of the obvious approaches to take is to automate control of the vehicle, thereby eliminating human error. Since the early 90’s this has been the approach of researchers developing Automated Vehicle Control Systems (AVCS). AVCSs promise to reduce or eliminate accidents while increasing travel time by increasing average speed and optimizing the route traveled. Unfortunately, because of the complexity of the task this attempt is a long way from fruition. Furthermore, there is a natural opposition of drivers to reduce their control over the vehicle that makes it difficult to implement any incomplete AVCS. As an example, a tested device already exists which can limit the speed of a vehicle. Despite the benefits of such a device, because of the expected opposition by drivers, it is not under consideration for widespread implementation.

One particular approach within the overview of AVCS has been to develop a system that warns a driver of a potentially dangerous situation but does not impose any control over or restrictions on him. The idea behind this is that it might be possible to reduce the frequency of accidents by alerting the driver when an accident is likely to happen. This is not as simple as it seems since such systems often have undesirable side effects such as increasing average speed and causing driver complacency. Nevertheless, some studies have shown that it is possible to overcome these obstacles with a carefully designed Collision Avoidance System (CAS).

A CAS is only useful for particular types of accidents. Road accidents generally fall into one of several broad categories based on the physical configuration and overall situation of the vehicles involved. These include front-to-rear, those resulting from a lane change (including merging), those at an intersection and those occurring during reversing. Allen, 1994 identified front-to-rear and lane-change collisions as being most easily identifiable and thus good candidates for a CAS. In particular, front-rear collisions are fairly frequent (accounting for 25% of vehicle crashes according to Knipling, 1994) and are primarily caused by driver inattention (57% in US Department of Transportation, 1995).

For example, a driver who has been driving for a long period of time may exhibit fatigue and lose concentration. Or, in a particularly dangerous phenomenon, a driver monitoring a visual scene may completely fail to notice a change of relative importance (such as a stationary object directly in front). This phenomenon is known as "change
blindness” and occurs when the subject is temporarily distracted from the scene or when the change happens away from the center of interest of the scene. The second major cause of front-rear accidents has been determined to be vehicles following too closely. In this situation, the following vehicle is simply unable to stop in time if the vehicle in front brakes suddenly. A suitable warning system can help to reduce accidents caused by either of these.

A CAS can use one or more of several available modalities: visual, auditory or tactile. The remaining two (olfactory and gustatory) are generally agreed to be unsuitable because of their complexity and their low latency. A lot of work has focused on the auditory modality, which has a long history of being used to provide alerts. It has been well documented that the response to an auditory alert is significantly faster than that to a visual alert. Furthermore in driving, the visual modality is often already burdened with the visual scene and the dashboard display. Research also shows that using an auditory alert together with a visual alert (particularly one superimposed on the visual scene) provides an even better alternative (Hirst & Graham, 1997).

The audio alerts used in experiments to-date have been non-localized (where the sound appears to be located within the head of the listener). This study seeks to determine whether localizing the sound at a more appropriate place (e.g. at the vehicle in front) makes any difference to these results. Also tested is a new type of audio alert that appears earlier but is designed to be less intrusive, increasing with volume as distance decreases.

1.2 Background

Several lines of research provide a theoretical background and make this project technologically feasible. At the most basic level Bechtel and Butter, 1988 showed that an auditory cue increases the speed of response to a visual target. Driver and Spence in a series of papers expanded upon this result in both the endogenous (voluntary response) and exogenous (involuntary response) domains. They explained this phenomenon in terms of overtly and covertly focused visual attention. Most recently they published a summary of research done involving cross-modal links (Driver & Spence, 1998).

This basic psychophysical result has lead researchers to explore the benefits of auditory spatial information in visual processing. A symposium on exactly this topic was held as a part of the Human Factors and Ergonomics Society 38th Annual Meeting in 1995. One of the papers from this symposium (Perrott, Cisneros, McKinley and D’Angelo, 1995) provided a baseline performance measure of aurally directed detection and search for visual targets. Their results show that capacity to process information from the visual channel was significantly sped up (10%–50% reduction in latency) when auditory spatial information was provided concurrently.

This shows that there is a valid psychophysical basis for using sound as an alert where immediate action is required. It further shows that a spatialized alert is superior to a non-spatialized alert where a visual search is required. Although in the case of a front-rear CAS the search space is one dimensional, spatialized sound may still be able to achieve a noticeable improvement. Also, using spatialized sound it is possible to provide earlier notice of a potential collision in a less intrusive and more natural manner by
representing the object in question by a sound source. It should even be possible to alert for potential collisions from behind. However, this has less tangible benefits since there is a very limited range of possible reactions to this information. As such, this is not considered in this study.

These results are interesting, but difficult to apply unless we can simulate spatial sound (appearing at an arbitrary location). The most obvious way to do this is to have a speaker at every possible sound location but this is almost always impractical. More often, we have speakers at several fixed locations (or perhaps headphones) and we would like to produce a soundscape that can fool a human listener into hearing a sound at any arbitrary location. In order to do this it is necessary to understand how human hearing, and in particular the perception of spatialized sound, works. Blauert, 1983 provides a good introduction to what is currently known concerning spatial hearing.

The next step is to use this information to produce a virtual soundscape – an environment in which the subject (or subjects as the case may be) perceives spatialized sound in a controlled way. These implementations are known as acoustic or auditory displays and have been discussed by Wenzel, 1991 and 1995 and more thoroughly by Garas, 2000. These displays have been used in several real-world applications including, tele-robotics and traffic collision avoidance systems. These applications show that the technology is sufficiently mature and advanced to enter into consumer-level products.

1.3 Approach

The main objective of this study is to investigate the feasibility of using spatial sound in a Collision Avoidance System (in particular in one designed for front–rear collisions). This is a simulator–based study, which means that it does not accurately reflect performance in actual driving situations and cannot be used in place of real-world road trials. Nevertheless, it is intended that the simulation be accurate enough to predict the likely performance of spatial auditory cues in CASs and give some general indication as to the potential usefulness of spatial auditory cues in assisting with complex visual tasks. In addition, no attempt is made to describe the actual implementation. It is assumed that, a sensor is available which will provide the distance and relative velocity of any object immediately in front of the vehicle in real time. This assumption is reasonable as such devices do exist.

This basic information (along with the absolute velocity of the vehicle) is used by several suggested alerts for CASs. Several recent studies have explored which of these are the most promising, examining characteristics and combinations that have been successful. This research was used in carefully designing collision alerts that drew on previous design experiences and comparisons, but at the same time seeking to take advantage of the additional flexibility conferred by being able to spatialize auditory alerts. Since experiments have shown that multi–modal alerts can be more useful, each auditory alert was tested with or without a visual alert. This resulted in a total of 6 CASs.

To compare the resulting CASs, they were integrated with a virtual driving simulator designed for this purpose. The simulator was designed to retain as many as possible of the characteristics that significantly affect the driving experience. For additional realism, a steering wheel and pedals were used in the simulator. Several
scenarios were crafted to be played out on the simulator. Each scenario consists of a short (less than 5 miles) route to be driven. Along this route or more of several events occurs, requiring the driver to react. The behavior of the driver during the task including speed, acceleration/deceleration and steering is monitored during the task and saved for future analysis.

To analyze the data, we draw on the work of Janssen & Thomas, 1997, who give a list of three parameters, which are generally agreed to characterize "safeness" of driving. They proceed to discuss characteristics of a "good" CAS in terms of these parameters, providing a foundation for our own comparison. The results are compared to results from similar experiments so they can be interpreted within the larger framework of ongoing research. Comparing the results with experiments using more elaborate simulators or real driving situations also helps to validate the performance and suitability of the simulator used in this study.

1.4 Organization

This thesis is divided into 5 separate sections. This is the first one that contains an introduction to the project and the motivation behind it. It gives a very brief background and summarizes the structure of the thesis. Chapter 2 goes into more detail on the background work done. This project covers several different areas ranging from auditory research to human interface design. Relevant background on the different applicable areas is given. This gives a solid theoretical foundation to the rest of the project.

Chapter 3 describes the design of the system – the alerts, the overall CASs to be tested and the simulator-based testing framework. The design of each is described separately, giving the factors considered and the rationale behind any design decisions made. At the end an overview of the entire system is given. This leads right into Chapter 4 which describes the experimental validation of the system. The experimental methodology is detailed, along with any precautions taken. The results are then presented along with an analysis and discussion of the results.

Finally, Chapter 5 concludes by summarizing what has been done and what has been determined and gives some possible future directions for research. The final sections contain a glossary of terms used in the thesis and a master list of references. Appendices contain any additional explanations, derivations and results too lengthy or detailed to be contained within the main body.
2 Background

2.1 Natural hearing

2.1.1 Introduction

In order to provide suitable auditory cues, it is necessary to investigate human hearing in some detail. In particular, we are seeking answers to the following questions:

- How do we hear and interpret auditory cues, and in particular auditory spatial cues?
- What are the limits of the human auditory system?
- How can we simulate these perceptions so as to make use of these abilities?

There is a considerable body of work on all three of these questions and it is useful to summarize the current state of knowledge before continuing.

Sound consists of a series of mechanical vibrations and waves in an elastic medium. Humans can hear sounds in the range of about 16 Hz to 20 kHz. Hearing is particularly acute in the region of frequencies which contains most normal speech – at about 200 Hz. Human hearing also covers an extremely wide range of intensities ranging from a minimum of 10–12 watts/m² to a maximum of 1 watt/m² (beyond this threshold, hearing becomes painful). This means that we can hear sounds varying over 3 orders of magnitude in frequency and over 12 orders of magnitude in intensity.

The loudest sound one can hear certainly does not seem to be a billion, billion times as loud as the quietest sound. This is because the auditory system uses a logarithmic system for measuring the intensity of a sound. There is a special system of units that corresponds more accurately to how loud a sound appears to be. The decibel is defined as one tenth of a bel where one bel represents a difference in level between two intensities $I_1$ and $I_0$ where one is ten times greater than the other. Thus, the sound level in decibels is the comparison of one intensity to another and may be expressed:

$$\text{Intensity level} = 10 \log_{10} \left( \frac{I_1}{I_0} \right) \text{(dB)}$$

The result of this logarithmic basis for the scale is that increasing a sound intensity by a factor of 10 raises its level by 10 dB and increasing it by a factor of 100 raises its level by 20 dB. 0 dB is an internationally agreed on standard corresponding roughly to the lower human threshold of hearing.
This impresses the fact that we need to make a clear definition between the physical characteristics of the sound source, and the characteristics of the auditory perception. Indeed, it is possible to have an auditory perception without a sound source (for example ringing in the ears) and vice versa (for example if no one is around to hear the sound). Auditory experiments are further complicated by the fact that we have access to neither of these objects directly: we only have access to the auditory perception via a subjective description and to the physical sound source only via other physical measuring devices. This is shown in Figure 1.

2.1.2 The Human Auditory System

The human auditory system is a moderately complex system beginning at the outer ear and ending with interpretation by the brain. The ear itself is normally divided into three sections: the outer ear, the middle ear and the inner ear. Incoming sounds interact with the fleshy part of the outer ear called the pinna (or auricle). It is a framework of cartilage covered with skin producing a distinctive relief that is unique to an individual. The resulting sounds are funneled down the ear canal, which is a slightly curved tube about 25 mm long and with an average diameter of about 7 mm. The ear canal is terminated by the eardrum. This is a thin, slightly elliptical, cutaneous diaphragm about .1 mm thick and 9–11 mm in diameter. It is sloped at about 45 degrees to the axis of the ear canal and separates the middle ear from the outer ear.

The eardrum transmits the sound to a series of three bones (the maleus, incus and the stapes) in the tympanic cavity, called the ossicles, which in turn transmits the sound to the inner ear. The eardrum is sensitive to pressure differences between the outer and middle ears, so the pressure in the tympanic cavity is highly regulated and variations of pressure in the middle ear alter our auditory perception. The ossicles serve to impedance match the air medium of the outer ear to the fluid medium of the inner ear, which has significantly different acoustic impedance. The ossicles also serve to amplify the sound pressure transmitted to the inner ear. It does this by virtue of the fact that the surface area in contact with the eardrum is 21 times as large as the surface area in contact with the cochlea. This leads to a corresponding amplification in the pressure transmitted.
The ossicles transmit the sound to a membrane-covered oval window in the cochlea setting up waves in the non-compressible fluid. The cochlea is circular, liquid-filled chamber, winding towards a central point. Ultra-sensitive hair cells along the curved path are sensitive to various frequencies, and transmit signals to auditory nerves connected to them. These auditory nerves carry these signals to the brain where the interpretation of the sounds and the actual perception occurs. The inner ear also contains organs for sensing movement and balance.

2.1.3 Spatial Hearing

Apart from easily definable qualities of a sound source such as loudness (intensity), pitch (frequency) and timbre (quality), humans can perceive more complex physical qualities of a sound source from the sound it emits. Humans can deduce with varying degrees of accuracy the distance and velocity of the sound source as well as some properties of the surrounding environment (for example whether a room is carpeted or not). The ability to predict the position and velocity of a sound source is the most important to us and we will be concentrating primarily on this spatialization ability.

The ability to judge the position of a sound source has been well researched. The
first theory explaining this ability was the classic "duplex theory" (Lord Rayleigh, 1907) which explained this ability in terms of cues depending on input from both ears (binaural cues): interaural intensity differences (IID) and interaural arrival-time differences (ITD). IID are caused by differing degrees of shadowing by the head and were theorized to determine localization primarily at higher frequencies above 1500Hz. ITD were thought to be important only for lower frequencies below 1500 Hz since phase ambiguities occur at higher frequencies. However, it was later determined that ITD can provide cues even at high frequencies if the signal has sufficient bandwidth that the interaural envelope time difference (IED) can be reliably computed.

Although these two cues have been confirmed to be important, there are several deficiencies in this theory. This theory cannot explain the ability of subjects to localize sounds on the median plane between the two ears, or the ability of subjects deaf in one ear to localize sound sources. Moreover, when subjects are presented with appropriate ITD and IID for spatialized sound sources over headphones, several ambiguities result, the most important being that sources are perceived as being inside the head (Plenge, 1974). These deficiencies suggest that other factors contribute significantly to spatialization.

More recent studies show that the most important of these factors is the interaction of the sound with the outer ears or pinna. The pinna reflects and refracts sounds in an effect that depends heavily on the direction (see Shaw, 1974) and the frequency of the sound. This filtering effect helps to discriminate location, and the presence of these cues improves localization ability (Oldfield & Parker, 1984), as well as being primarily responsible for auditory externalization (Plenge, 1974).

Even when interaural and pinna filtering cues are available, for example for a non-moving head in an anechoic environment with non-familiar sounds, various confusions arise when trying to discriminate location of a sound source which do not normally arise. In particular, subjects in such constrained conditions experience front-back reversals (e.g. determining the position of a source in front to be in the back), right-left reversals (Oldfield & Parker, 1984) and up-down reversals (Wenzel, Wightman & Kistler, 1991). This probably results since the pinna cues are not as strong as the IID and ITD cues that have inherent ambiguities. Assuming a simple spherical model for the head, sources having a given ITD or IID lie on a conical iso-ITD or iso-IID surface that results in contours of confusion. Although this is not completely accurate, this suggests that these cues are ambiguous.

Additional information is available for a sound source that is moving. For a laterally moving sound source in front, the IID and ITD change in opposite ways compared to the change for a source in the back. In addition, simple monaural cues are available from the additional information such as amplitude changes and a Doppler shift effect. Rosenblum, Carello & Pastore, 1987 showed that each of these three cues is successful in helping a subject determine when a moving sound source passes him. They also found that the amplitude change cue dominates the ITD change cue, which in turn dominates the Doppler shift cue.

For the intensity of the sound to be used as a monaural cue for distance, the sound source has to be a familiar one to the subject. In fact, if the sound source is familiar
several other cues are available. For example, the inter–head localization confusion is significantly reduced with a familiar sound (Gardner, 1968) and distance judgments are much improved (Laws, 1972). Also, familiarity with the spectrum of a given sound source can assist in spatial localization of the source from monaural input, in people deaf in one ear for example.

Finally, the perception of location is affected by environmental effects. This effect occurs because sounds get reflected and refracted by the surrounding environment in a complex way that can result both in a filtering effect as well as several echoes. This effect is fairly complex and can actually interfere with perception of a sound source (Blauert, 1983) especially in the case of significant echoes. This effect, however, is reduced by the phenomenon known as "precedence". In this phenomenon, the perception of direction of a sound source is dominated by its initially incident wavefront. The effect of following echoes is diminished, even if they would normally indicate additional sources in different locations. There is also research that shows the benefit of environmental cues in reducing inter–head localization (Plenge, 1974).

This shows that the determination of the location of a sound source purely from auditory cues is very complex. In an artificial system that simulates 3–dimensional sound, these cues have to be taken into account in order to produce sound that is both accurate and realistic in its spatialization. The reference on spatial hearing is the in–depth review by Blauert, 1983 but Wenzel, 1992 provides a more up–to–date summary with a focus on information relevant to auditory displays.

2.1.4 Auditory–Visual Connections in Attention

Basic cross–modal (concerning more than one sense) research has shown that auditory cues can contribute to visual attention in several ways. A spatial auditory cue improves the accuracy of and time taken for visual judgments in the direction from which the sound originates. It also reduces the simple reaction time to a visual target (Buchtel & Butter, 1987). These benefits occur for both exogenous events (that happen unexpectedly and are reflexively captured) and endogenous events (that are expected and consciously scanned for) (Spence & Driver, 1996 and 1997).

Higher level research shows that these advantages extend to the detection and identification of visual targets. In Perrott et al (1995), presenting a spatially correlated audio cue together with a visual target reduced the latency time for detection by between 10 and 50%. Perott, 1988 observed that even for targets as close as 10 degrees from the line of view, the response time to a target was reduced by 15–10% with much larger improvements for larger lateral displacements.

2.2 Spatialized Audio

Traditional forms of stereo sound are in fact a simple form of sound spatialization. Spatial information is presented primarily by left–right intensity panning which enables approximate localization of a known stimulus along the line joining the two speakers. This technology is omnipresent in consumer audio electronics.

Auditory researchers quickly realized that to present more accurate spatialized sound they would have to reproduce the effects of IID, ITD and the complex filtering
effect of the pinna (and the shoulders etc.). It turns out that all of these effects may be cumulatively represented as a single filtering operation. This operation applies a filter to any input sound, which transforms it based on its frequency and spatial position to two streams suitable for playback over headphones.

For one particular position, this may be measured in an experiment in which a high-bandwidth sound such as a click is produced by a loudspeaker at that particular position. The sound heard at a subject’s ears is recorded is measured by small probe microphones inserted into the subject’s ears. Using these two responses together with the input signal, it is possible to calculate two filters which contain all relevant spatial cues for a given source location, a given listener and a given room or environment (normally chosen to be anechoic).

These filters are examples of finite impulse response (FIR) filters and are often referred to as head–related transfer functions (HRTFs). If these HRTFs are calculated for many positions on a sphere surrounding the listener, it is possible to interpolate for any position on a sphere the required filter. Most 3D audio systems use a standard set of HRTF’s based on a model (such as KEMAR in Gardner & Martin, 1997) or based on averaging the responses of several human subjects.

This approach works reasonably well for reproductions over headphones. But quite often it is desirable to use a pair of speakers instead of headphones. In this case, ideally we want the left speaker to provide the signal that the left earphone would have and similarly on the right. Unfortunately, this does not normally happen since the left ear also hears the output from the right speaker and vice versa. This can be solved by computing the matrix that represents these cross-talk signals and passing the signals through a filter that inverts it (Atal & Schroeder, 1962).

Although there has been a tremendous amount of work on reproduction of 3D audio, there has been less work done on psycho–physical validation. Wenzel & Kistler (1991) used 16 inexperienced listeners to compare the localization of actual positioned loudspeakers with virtualized sources created using a fixed HRTF and presented over headphones. The results showed that inexperienced subjects are almost the same for virtualized sound with two exceptions. Elevation judgments were significantly worse for 2 of the subjects and the ratio of front–back reversals was increased for the virtualized sources. Interestingly, Asano, Suzuki & Sone (1990) showed that the reversals tended to diminish for experienced subjects even without feedback. The research used the HRTFs of a subject who had above–average localization ability and did not measure ability to judge distance, which is much more complex.

### 2.3 Causes of Crashes

It is worthwhile to refocus temporarily on the underlying goal of this study: reducing the frequency of rear–end crashes. To do this it is beneficial to review the current frequency and causes of crashes. The US Department of Transportation, 1998 tells us that every year vehicle crashes in the US account for more than 3 million injuries, over $130 billion in financial losses and over 40,000 deaths. This is a staggering toll despite impressive improvements made in in–vehicle safety (such as air bags and seatbelts) and in the overall rate of fatalities (which have decreased from 5.5 in the 1960’s to 1.7 in 1994).
Najm, Mironer and Fraser, 1995 categorize accidents into 8 categories depending on the situation occurring immediately before the accident. These are: rear-end, reversing, lane change including merge, single vehicle roadway departure, opposite direction, left-turn across path, signalized intersection and unsignalized intersection. Rear-end accidents are the most frequent, accounting for 28% of all vehicular accidents and causing approximately a third of all delays resulting from accidents (National Safety Council, 1996). This motivates our restriction to rear-end collision detection.

<table>
<thead>
<tr>
<th>Causal Factor</th>
<th>% of Rear-end Accidents Caused</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inattention</td>
<td>56.7</td>
</tr>
<tr>
<td>Tailgating/Unsafe Passing</td>
<td>26.5</td>
</tr>
<tr>
<td>Ill</td>
<td>9.6</td>
</tr>
<tr>
<td>Bad Roadway/Surface Conditions</td>
<td>2.3</td>
</tr>
<tr>
<td>Drunk</td>
<td>2.1</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>1.3</td>
</tr>
<tr>
<td>Vehicle Defects</td>
<td>1.2</td>
</tr>
<tr>
<td>Misguided Gap/Velocity</td>
<td>0.4</td>
</tr>
<tr>
<td>Reduced Visibility/Glare</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1: Causes of Rear-end Accidents (Naim et al, 1995). Total is more than 100 percent owing to rounding errors.

Rear-end accidents can be further classified by the causal factors. Table 1 (from Najm et al, 1995) gives this breakdown employing a taxonomy they developed. Unfortunately their classification hides some of the details. For example, an unrevealed fact is that 19.4% of rear-end crashes were explained by both driver inattention and tailgating (these were subjectively chosen to be listed under the tailgating section). We examine their results under 4 categories, which are more appropriate to this study: illness/inebriety, driver inattention, driver misjudgment/tailgating and environmental factors. These are not distinct or disjoint as the cause of an accident is often a blurred combination of different factors.

2.3.1 Driver Inattention

Since driving is such a visual activity, a tremendous amount of information is prevented to a driver visually. Of this large amount of information, he must choose the most immediately relevant items to attend to. Inevitably, occasionally events that should be attended to are not for example an approaching, speeding car or a stationary car in the road ahead. In an extreme case, a driver may fail to attend to an object directly in front of him. This may happen if he shifts his gaze temporarily or if he is attending to a different
part of the scene. This is known as "change-blindness" and has recently been the focus of some attention.

This case is the most easily remedied by an appropriate alert. Once the driver is alerted to the potentially dangerous situation, he should be able to deal with it adequately unless one of the other factors comes into play. This case accounts for around 55% of all rear-end accidents providing further motivation that a suitable CAS (even one targeted only to his cause) can significantly reduce the frequency of accidents.

Assuming that it is possible to identify these potentially significant events, the perfect way to present them would be via auditory cues. The use of sounds to present alerts is well known and has a solid theoretical background. It is widely believed that the acoustical information serves primarily as a cue to direct visual attention (Schiff & Oldak, 1990). Guski, 1992 supports this and suggests that acoustical estimates of time-to-contact of an approaching object are too inaccurate to be used directly, but can be used to determine whether there is time to visually focus on the object before reacting.

2.3.2 Illness/Inebriety

These two factors may be very different, but they have the same net effect: they both affect a driver’s physiological state negatively. This may result in reduced, slower responses, increased misjudgments and difficulty in visually focusing and attending on the scene. Suitably timed alerts can help to alleviate the misjudgments and help to focus attention when needed, but are unlikely to assist with reduced responses. Collision alerts are generally designed to give just enough time for a person with regular physiological responses to react. Giving more time than this results in too frequent alerts which may annoy a driver and have detrimental effects on his driving behavior. Collision alerts can thus help to reduce accidents caused by illness and inebriety, but not completely. Even with alerts, inebriated or ill drivers should stay off the road, but considering that around 10% of rear-end accidents result from one of these factors, this is highly unlikely.

2.3.3 Driver Misjudgment / Tailgating

These two are almost indistinguishable from each other. If a driver misjudgment leads to a rear-end collision, he probably was tailgating. Conversely, someone who is tailgating another vehicle is probably doing it because of a misjudgement and not deliberately. This is the most prevalent cause of rear-end accidents after driver inattention, causing roughly 25% of rear-end accidents. An alert can help to ensure that tailgating cannot occur. It is relatively easy to calculate the "headway" of a moving vehicle which is the distance it needs to come to a complete stop, and to trigger an alert when there is another car within this distance.

This simplistic measure, however, is overly conservative as it does not take into account the fact that the vehicle in front may be moving as well. In the next section we will discuss some of the issues that arise when considering exactly when to trigger an alert. Apart from a triggered alert, a continuous representation of the headway may be able to help alleviate this misjudgment. Alternatively, a continuous representation along with a triggered alert has shown even more promising results (Hirst & Graham, 1995).
2.3.4 Environmental Factors

These are factors that are independent of the car or its driver. Inclement weather conditions and bad roads fall under this category. Bad road conditions are likely to thwart the effect of a CAS, since a CAS assumes ideal road conditions in deciding when to trigger. Since the braking distance in adverse weather or road conditions is likely to be greater than normal, a CAS would not be able to prevent these accidents without using sensors detecting the condition of the road. This is unlikely for the first generation of CAS devices.

However, a suitable CAS can help to prevent accidents due to adverse visibility. An appropriate alert can alert the driver of a potentially dangerous object in front even if the object is invisible or obscured by weather conditions or darkness. This is confirmed by Janssen and Thomas, 1995, who also showed that empirically, a CAS that is effective under normal conditions is also likely to be effective under adverse visibility conditions.

2.4 Collision Avoidance Systems

2.4.1 Introduction / Background

Recent advances in active sensor technology and human factors research have combined to make systems combining collision detection and warning a technical possibility. Systems combining both of these components (detection and warning) are known as Collision Avoidance Systems. The objective is to alert the driver of potentially dangerous situations thereby reducing the risk of accidents. This section summarizes what has been done thus far in the development of CASs.

An early application of CAS occurred in the aircraft industry, which developed the Traffic Collision Avoidance System. Cockpit crews use this to alert them of aircraft in the surrounding volume. The TCAS alerts pilot crews to three sets of information: proximate traffic (not urgent but just for informational purposes), traffic advisories (when a collision is calculated to occur within 40 seconds) and resolution advisories (when a collision is calculated to occur within 25 seconds). In the current TCAS implementation, there is an auditory verbal warning, but all spatial information is provided by a visual head-down display, which must be scanned after hearing the alert. TCAS II, which implemented these features, became mandatory on US commercial aircraft in 1994.

Recent work to improve this system was done at the NASA Ames Research Center, where researchers built a heads up auditory display and integrated it with a cockpit simulator. The display used headphones and was used to augment a typical TCAS implementation. Begault, 1993 showed that replacing the visual head-down display with auditory spatial information reduced the time taken for visual acquisition of the target by an average of 2.2 seconds.

Automotive CASs are not quite as developed, probably because the motivation in the airline industry to implement an effective CAS has increased with every aircraft collision. Nonetheless, there has been steady progress. National Highway Traffic Safety Administration (NHTSA) modeling of traffic collisions has predicted that "head–way detection systems can theoretically prevent 37% to 74% of all police reported rear–end crashes." With rear–end crashes accounting for over 25% of all accidents, even a simple CAS would be readily accepted, once it is effective and acceptable to drivers.
With this in mind, the Automotive Collision Avoidance Systems (ACAS) Program was launched in 1995 as a two-year study to provide a "focused approach to accelerate the development of active collision avoidance systems" (NHTSA, DOT HS 809 080). It consisted of nine U.S companies: recognized leaders in their respective fields of expertise in the technology, manufacturing and marketing of collision avoidance products. Their long-range vision is for a system using three main components: long range radar or optical sensors to detect potential hazards in front of the vehicle, short range sensors to warn the driver of nearby objects when changing traffic lanes or backing up, and a lane detection system to alert the driver when the vehicle deviates from the intended traffic lane.

Such a system would need to have in addition, a reasonable price, effective functionality, a non-intrusive nature and reliable, robust performance. They developed several building blocks for the construction of such a system including active sensors suitable for remote-object detection, collision warning algorithms and a suitable Heads-Up Display (HUD). They also did a considerable amount of work on human factors in determining the most suitable of several types of alerts. However, they stopped just short of any integration into a complete, seamless system.

The development of any automotive CAS is complicated with a number of factors that must be considered in any study. While the primary goal of a CAS is to avoid crashes, it is not always evident how to tell that this effect is being achieved. Indeed, some obvious measures of crash frequency and driving safety fail to give the entire picture.

For example, a tested CAS might reduce the proportion of short headways (situations where the vehicle is too close to the one in front). However, this might have several unintended effects. Drivers, who are annoyed by the CAS alerts, might behave erratically (frequently accelerating and decelerating or changing lanes) to avoid them. This behavior could actually increase the frequency of collisions. Drivers who feel an additional sense of safety imparted by the CAS might become less attentive to the driving task, relying on the CAS to alert them of dangerous situations before they become hazardous. Reliance on the CAS and less attention paid to the driving task would very likely lead to unsafe driving habits and behavior.

To attempt to quantify these effects, Janssen and Thomas (1995) came up with a tentative list of three parameters which taken together could be used to describe the safety of driving behavior. These are:

- the distribution of headways between the CAS vehicle and the vehicle leading it (in particular the proportion of short headways below 1.0 seconds or .5 seconds)
- the distribution of speed of the CAS vehicle (especially the fraction of time at higher speeds)
- the distribution and frequency of accelerations and decelerations (especially the momentary ones which may not be necessary or safe)

The primary behavioral motivation of CASs thus far has been to reduce the proportion of short headways. Janssen and Thomas suggest therefore that the effectiveness of a CAS be judged based on how well it does this, while minimally suffering from counterproductive effects. They also later suggest that another measure be taken into account: the frequency of changing lanes or the proportion of time spent in the overtaking lane. This measure was
added because in driving simulations, drivers have been observed to attempt to evade CAS alerts by spending more time in the overtaking lane – definitely an unsafe practice.

2.4.2 Collision Activation Criteria

The first part of any CAS system is a detection component. Enough work on this has been done that we can be confident that, within reasonable limits, the speed and distance to a sufficiently large object in front of a vehicle may be determined with adequate accuracy. The next problem of a CAS is to decide, given this information, when an alert should be presented. In other words: how close is too close? If, on the other hand, a continuous representation is used, this problem does not arise.

Selection of a suitable criterion is a complex question that has not yet been adequately answered. The effectiveness of such a system depends on its ability to reliably and consistently predict the paths of the objects involved in the interaction as well as the ideal reaction of the driver. Unfortunately, there is a fundamental tradeoff between reliability and validity. If a CAS can reliably predict dangerous situations in time for the driver to react, it tends to have a high rate of false alarms, where it alerts for situations that are not seen as dangerous. This negates the effect of the CAS since it leads the driver to be unconfident in the CAS and to ignore its future alerts. On the other hand, a CAS that has a high validity and very few false alerts tends to be unreliable and miss a significant proportion of dangerous situations that should trigger alerts.

Several criteria have been suggested to decide when to trigger a response. Janssen, 1989 divided criteria into three groupings based on what information is used to calculate the activation trigger. Criteria which only require knowledge of the velocity of the CAS vehicle are identified as fixed in nature. They are the most conservative, since they do not take into account the movement of the target vehicle. Criteria which do take into account the movement of the target vehicle are termed momentary. The last category are conditional criteria which contain combinations of fixed and momentary criteria applying simple logic to choose between them. We discuss each of these categories in turn.

Fixed Criteria

Practically the main example of a fixed criterion is the headway criterion. "Headway" is a measure of how much free space is in front of the vehicle. This has two incarnations. Headway given in units of length, imply a fixed distance of free space (i.e. a buffer) in front of (or around) the car. If any object intrudes within this space, an alert is triggered. Headway can also be given in units of time. This is similar except that the free space distance varies with the speed of the car (buffer distance = headway time x speed of vehicle). Thus a vehicle traveling faster will have a larger buffer and an alert will be triggered sooner.

The headway criterion has the advantage that it can be measured with a high degree of accuracy and is a measure that is natural to the driver. It has been generally found that if a driver understands the basis of a CAS, he is more likely to cooperate with it and be amenable to the benefits. It is hypothesized that unnatural criteria lead the driver to be unsure and unconfident of the CAS, leading to a lack of trust in its judgment.

As the simplest possible valid criterion, headway was the first used in CAS studies. This quickly proved to be too simplistic, resulting in an unacceptable number of
false alarms (Janssen, 1989). Janssen argued that this shortcoming cannot be overcome. The headway also ignores situations where the braking distance or time may be increased. By itself, it is thus ineffective in inclement weather other bad road conditions.

Given its unsuitability as a trigger alert, McGehee, Dingus and Horowitz (1994) proposed a continuous representation of headway as an informative display for the driver. Their display consists of a trapezoid, split into 9 horizontal bars. The number of bars displayed depends on the headway from the closest vehicle. The bars have different colors; the top three are green, the second three are yellow and the bottom three are red. Hirst and Graham (1995) achieved good experimental results with a similar display (combined with an alert).

Momentary Criteria

The most basic momentary criterion is the Time-to-Collision (TTC) criterion. This assumes that the following and leading vehicles will maintain the same velocities for the immediate future. If a collision is imminent within a certain period of time, an alert is triggered. More concisely, assuming that the vehicles are traveling in the same line:

\[
TTC \ (sec) = \frac{\text{Distance apart (feet)}}{\text{Relative speed (feet/sec)}}
\]

This criteria has been very popular among CAS researchers because it is simple to calculate and has a very low frequency of false alarms. The TTC criterion is much less conservative than the headway criterion. Unfortunately, it is a bit too liberal in what it allows. Two vehicles traveling at the same high speed, but very close together would not trigger an alarm because the relative speed is zero and a collision is not imminent. However, clearly this configuration is a dangerous one and should trigger some sort of alarm. This shortcoming could lead drivers to become reliant on the CAS and actually reduce their following distances.

Van der Horst (1984) found that a TTC of 1.5 seconds identifies configurations that have become critical. He also found that a TTC of 4 seconds could be used to discriminate between cases where drivers found themselves in a dangerous situation from cases where drivers retained control of the car. He thus recommends 4 seconds as the criterion for a first alert. Farber (1991) supported this, suggesting that it makes the correct tradeoff of high reliability for high validity i.e. it is less likely to trigger but more likely to correctly identify a dangerous situation when it does. However, since drivers normally begin braking at around a TTC of 4 seconds (Maretzke and Jacob, 1992) this may be a bit short since it does not allow time to react.

The ideal CAS will alert the driver to a dangerous situation just before he would have normally reacted if he was in full control. With this in mind, Hirst and Graham, 1994 did an experiment to find out how late drivers reacted to a sudden deceleration of the vehicle in front. They found that the time of braking was not at a fixed TTC but followed the equation

Minimum judged safe braking distance = distance predicted by a TTC of 3 sec + 1 foot per mile per hour of vehicle speed
They concluded that a TTC of 5 seconds gave too many false alarms, but a TTC of 3
seconds probably allowed insufficient time to brake. They suggest using a TTC of 3
seconds added to their empirically determined factor of 1 foot per mile per hour of vehicle
speed.

**Conditional Criteria**

Conditional criteria have been attempts to improve on the shortcomings of the
TTC criterion, but deciding exactly how to improve this has been difficult and largely
unsuccessful. Janssen and Thomas (1995) tested a "worst-case" criterion which alerted
when either a TTC of 4 seconds or a headway of 1 second was reached. This combination
was more conservative than either criterion by itself. This criterion proved less
ineffective than a straight TTC of 4 seconds. Janssen and Thomas hypothesize that drivers could not
understand or predict the alert leading to a lack of faith in the system. Janssen and Nilsson
(1990) obtained similar negative results for another different conditional criterion.
Although conditional criteria are, in theory, promising replacements for a normal TTC
criterion, it seems evident that not enough work has been done to confirm a superior
replacement.

2.4.3 Types of Alerts

The final component of a CAS system must present the information to the driver in a
suitable way. The information may either be a triggered warning or continuous display of
information. Much human factors research has been devoted to determining the most
effective and least intrusive way to present this information. This has been primarily
focused on the auditory and visual modalities with recent (but promising) work done in
the area of tactile feedback. We give a brief summary of this research, categorized by the
modality used to present the information.

- **Visual**

  Visual alerts are comfortable and well known to the driver. Vehicles normally
come with an increasing array of visual alerts, identifying such problems as: fuel
shortage, overheating, open doors, broken lights, oil shortage and seatbelts not in use.
This has clearly been rather effective for the uses to which it has been put. The problem is
that additional visual alerts buried in such a bewildering of visual feedback my go
undetected. For a CAS alert, this is unacceptable. This problem can be countered
by distinguishing CAS information by presenting it in a heads-up mode i.e. superimposed on
the scene. This has the additional advantage of being visible to the driver while driving
without looking down and, if presented properly) do not even require the driver to
refocus.

  This Heads-Up Display (HUD) has been generally agreed on to be most effective
for CAS information compared to the other two alternatives: mid-head and head-down or
dashboard displays. However, even these have the problem that they place additional
work on the driver’s already overburdened visual system. Especially during a high-load
driving task, the additional stress of monitoring a visual alert might be counter-effective.
Verwek (1991) proposes that the visual load of a driver be monitored and visual
information be presented depending on this load, but this is inapplicable for urgent alerts as these will most likely be necessary when visual load is high and must be presented.

Theeuwes and Alferdinck (1995) showed that a high-mounted brake light elicited a faster response than either a low-mounted one or a lack of one. Sivak et al. (1981) in a similar experiment observed that the number of reactions was greater with a high-mounted brake light, but the reaction time did not differ. On the other hand, Hirst and Graham (1995) showed that a continuous HUD of headway does not improve the safety of driving behavior (also Janssen and Thomas, 1995) and neither does a pictorial warning. They hypothesize that the continuous display by itself does not present any useful information by itself. The pictorial display, which performed much worse than an abstract visual alert, could have performed badly because it required a significant amount of time to interpret, adding to the driver's visual load. They achieved the most safe driving behavior with a combination of an abstract visual alert and an auditory alert (discussed below).

- Auditory

In contrast to the visual modality, the auditory modality seems to be relatively unburdened during any driving task. Modern vehicles typically shield drivers from almost all of the sounds in his environment and the engine. Auditory alerts also have the advantage that they are hands-free and eyes-free, allowing a driver to monitor for alerts while visually and manually engaged. They can also be perceived in adverse visual conditions and can be used to represent both discrete and continuous information.

There are however several practical difficulties to implementing auditory alerts. Individual differences in hearing acuity are much greater than corresponding differences in visual acuity making it hard to develop a standard default setting that would be equally effective for a wide range of consumers. In addition, hearing acuity is not required (by law or in practice) and relying on auditory alerts would put hearing-impaired drivers at an unnecessary disadvantage. There is also extreme variability in the amount of sound/noise present in a driver's atmosphere including the following sources (with varying volumes): entertainment (radio/media), CB radio, engine sounds and cellular phones.

Despite these drawbacks, the advantage of auditory alerts over visual alerts make them attractive choices in certain cases. Properties of messages that make them amenable to an auditory alert are (Deatherage, 1972):

- brevity and simplicity - short, simple messages are the best candidates to be expressed with an auditory alert
- requirement for immediate action - auditory alerts are good for cueing for immediate action since they are reacted to quicker
- presented to a visually overloaded subject - if a subject (i.e.) driver is visually overloaded, an auditory alert would be easier to identify
- use in adverse visual conditions
- use by a subject that is constantly moving - because of the hands-free and eyes-free nature mentioned above

The siren of a police vehicle or ambulance warning drivers of their approach is a good example that satisfies these criteria. While auditory alerts are useful, overuse can lead to annoyed users disabling or ignoring the alerts. Multiple auditory alerts need to be easily
discernible and distinguishable from each other (Patterson, 1982), but may be undesirable because of the time needed to learn and become familiar with them.

For a CAS, little or no learning should be necessary and it should be as intuitive as possible what an alert is for. Edworthy, Loxley and Dennis (1991) performed a series of experiments to determine what types of sounds are naturally perceived as urgent. They came up with a list of properties of a sound make it be perceived to be urgent. Haas (1993) elaborated on this by quantifying the properties. Details of this are given in the design section.

One way of providing easily discernible, distinct messages via audition is using speech. Speech has the advantage that is has already been learned and can take advantage of the benefits of the auditory modality. Despite this, speech has not had success for CAS alerts. Subjects have found speech to be the most annoying and intrusive type of alert and generally experiments using speech to provide CAS alerts have had negative results (Hirst and Graham, 1995). Speech is more suitable for environments where several different alerts must be provided or where the message to be conveyed is complex, requires specific action or is not fixed (Deatherage, 1972).

Another interesting possibility for auditory alerts is the use of "earcons". These are short sounds designed to mimic the sound of an actual object, for example an earcon of a church bell, or of a tire skid. The use of earcons attempts to solve the problem that users exposed to an unfamiliar sound may not know what the sound represents. This may affect the ability of the alert to trigger a quick response. Belz, 1995 proposed a technique for systematically identifying suitable candidate earcons for CAS systems and tested the most promising ones he found. He was able to show that using earcons as auditory alerts give consistently better results for front-rear CAS than using abstract sounds.

• **Tactile**

The tactile modality was the last of the three modalities to be used for CAS alerts, but it has quickly proved to be very promising. In one simulator study by Janssen and Nilsson (1991), they compared several different CAS alerts: a continuous visual display, a warning light, a warning buzzer or a "smart" gas pedal. The "smart" gas pedal provided tactile feedback by applying a 25N increase in pedal force whenever the warning criterion was met. The smart gas pedal resulted in a reduction of short headways while suffering the least from the dangerous side effects of increased speed and erratic driving.

Janssen and Thomas (1995) obtained similarly successful results for a smart pedal with a fixed TTC of 4 seconds. This combination reduced the average speed and proportion of short headways in both normal and decreased visibility conditions. The other two alerts were a HUD and a smart pedal with a "worst case" criterion and both resulted in increased average speed and increased or similar proportions of short headways. These two studies show that appropriate tactile feedback can be particularly effective in presenting urgent alerts.

• **Combined-modality**

Given that a single modality may be overloaded or that an alert given in a single modality may be unclear or undetected, the natural solution is to try presenting an alert simultaneously via more than one modality. The idea is that by providing redundant
information via different sensory channels, a warning is more likely to be detected and reacted to. Because tactile feedback is still new and not understood, most cross-modal CAS alerts have tried to combine visual and auditory alerts. This combination has often proved to be synergistic providing much better results than either of the alerts alone.

Hirst and Graham tried combining either of an abstract or a pictorial visual alert with either of a speech or non-speech auditory warning. They found that abstract visual alerts together with speech or non-speech warnings were successful in reducing the number of collisions and increasing the braking time before a potential collision. Belz (1997) found that presenting a visual display along with an auditory warning resulted in fewer collisions than with just the auditory or visual warning alone.

Despite the promise shown by these combined alerts, there is a lack of research that compares them to corresponding single modality alerts in the same experiment. Hirst and Graham, did not use include visual or auditory alerts by themselves leaving it to speculation that these wouldn’t have been as effective as the combined modality alerts. This study will attempt to confirm and quantify the benefits of using combined-modality alerts to using single modality alerts.
3 Design and Implementation

3.1 Research Objectives

This section will summarize what has been discussed in the last few sections about the state of development of automotive CASs and clearly outline what this study attempts to achieve. The development of automotive CASs has not progressed as quickly as it might have (for example aircraft CASs). This is despite the increasing use of the automotive human display to provide feedback to the driver, for example door-open visual warnings or reversing auditory warning. Despite this research has shown that a suitable CAS can be used to reduce collisions while resulting in safer driving.

Properties of an effective CAS are being gradually uncovered. For example, it has been discovered that a CAS using a TTC of 4 seconds as a trigger criterion can be effective. Likewise, the most effective alerts are gradually being developed from several modalities and a wide variety of presentation types. However, there are several gaps in the research into CAS alerts. Our objective is to fill in some of these gaps.

The first notable gap is in auditory alerts. Although it has been determined that auditory alerts (in combination with alerts in other modalities) can be effective and it has further been determined that non-speech alerts are more suitable since they are perceived as less intrusive. It has even been determined that particular abstract sounds are perceived as more urgent and that earcons which mimic sounds of real objects may be more effective than abstract sounds. What has not been explored is the effect of spatializing the sound alerts.

There is good reason to believe that spatializing an alert might result in a faster response to it as it is much clearer what the alert refers to, reducing the interpretation time. In addition, spatializing an alert gives the additional flexibility of being able to present continuous data via an auditory display. For example the headway of the leading car is easily and naturally represented by a sound source approaching the driver. This continuous presentation might be less intrusive than a sudden unexplained alert and might help the alert to seem less abrupt and jarring.

The main objective of this study will be to determine and quantify the effect of spatializing an auditory alert. For the audio alert, we will use an abstract sound determined to best express urgency to the subject. Although the use of sounds that mimic natural sounds is promising, we do not include these in our study. We also investigate the use of a spatial auditory cue that presents continuous data to the driver. Because this has not been attempted before, we need to design this alert before testing it.

The secondary objective of this study is to quantify the effects of using a multi-modal alert. Although it is generally agreed that multi-modal alerts are better than alerts presented in one modality only, there have not been many attempts to compare the effects of multi-modal alerts to the effects of their component alerts. In the course of investigating the effects of spatial auditory alerts, we examine 3 multi-modal alerts and compare them to the component alerts composing them. This quantifies the effects of combining alerts and may help to understand better the effect of combination.
3.2 Experimental Apparatus

3.2.1 Overview of Experimental Setup

Most automobiles today come with an audio system capable of simulated surround sound and consisting of 4 speakers. It is envisioned that any audio cues including spatial cues could be provided using this system, over any audio entertainment. To supply the spatial information required for a front–rear CAS, a car would need to be outfitted with sensors detecting the position and relative speed off the vehicle in front. There are several ways to do this including long–range radar and optical sensors (along with some sort of scene analysis). This information will have to be processed by an onboard embedded computer which processes the sonar data and filters the essential information. This can then be fed through a DSP chip, which can convert this information into suitable audio. Figure 3 shows what a front–rear CAS might look like for a consumer vehicle.

Although this is the intended use of the system, for testing purposes the CAS was implemented together with a simple driving simulation. This serves several purposes. A driving simulation gives a great deal of control over the setup for testing purposes. It is relatively easy to monitor the subject’s reaction completely, whereas on a real system this would require the setup of extra sensors. A driving simulation is also much faster to develop as a prototype, since it does not require a large amount of hardware modification.

The driving simulation consists of a steering wheel, pedals and one or more monitors representing the front windshield view. Optionally it is possible to simulate the rearview or side–view mirrors. Figure 4 shows the layout of the simulator setup. The subject will be presented with a simple driving task and his reactions and performance will be closely monitored. Quantitative ways to judge the quality and safety of a driving have already been discussed. Parameters in safety evaluation include headway from the car in front, time to collision, speed, acceleration/deceleration and amount of overtaking. All of these statistics would be easily and readily available from the simulator.

3.2.2 System Components

- Computer – A single pentium III 1GHz computer was used to both present the simulation and collision alerts and to collect the subjects response and behavior. The
simulation was presented on a single square monitor, 19 inches on a side, roughly 12 inches in front of the subject. This means that it was possible to simulate a field of view spanning 77 degrees. The video subsystem was powered by an ATI Rage video card.

**Figure 4:** Overview of Simulator setup

- **Soundcard and Speakers** – An important piece of hardware is the hardware which does the spatial audio processing. For the purposes of this equipment it was decided to go with a consumer computer soundcard (Hercules Game Theater) which has the required capabilities. There are several reasons for choosing this over the alternative solutions (do all audio processing in software, use dedicated hardware). Dedicated hardware tends to be very costly and the improvements in quality are questionable. Consumer soundcards are also probably a better indicator of the technology that is likely to be used if the system is actually implemented in a car. Finally, these cards have been used widely and successfully (on recent computer games) to perform the same type of 3d sound tasks required here.

  The other piece of audio hardware is the speakers. It was decided to purchase a 4-speaker setup since this is better for front back spatialization (this does not preclude the option of using only the front two speakers). The quality of the speakers is more than sufficient for this experiment. The model used was the Logitech Soundman Xtrusio Computer Speakers.
- Steering Wheels and Pedals – The final piece of specialized hardware is the steering wheel / pedals combo. These were purchased off the shelf based on their reviewed ability to mimic the feel of a real car. The model used was an ACT Labs Force RS Steering Wheel and Pedals. Although the pedals were used successfully in the experiment, it was unfortunately not possible to use the steering wheel, which was significantly more difficult to control than a real steering wheel.

- Software – We needed software that could create a 3d virtual world with an associated soundscape. The development had to happen fairly quickly and needed to be able to make use of the special hardware (steering wheel and pedals). We chose VisualC++ for the development. The visual virtual world was be done using the OpenGL and the audio effects were done using Microsoft’s DirectSound libraries.

OpenGL is a 2D/3D graphics API controlled by the OpenGL Architecture Review Board. It is strictly a graphics API but can be combined with other commercial or freeware products to make full-fledged applications. Other advantages of OpenGL are that it is relatively easy to learn and there are many tutorials and code examples available, many concerning 3D world development.

For the audio effects, we initially considered using OpenAL. OpenAL is a newly formed, open, vendor-neutral, cross-platform API for interactive, primarily spatialized audio. It resembles the OpenGL API in coding style and conventions. Sample implementations are provided for several platforms. Unfortunately, this proved to be a poor choice because the implementation available was immature, incomplete and not well-documented. DirectSound proved to have none of these shortcomings.

Programming of the pedal and steering wheel was done using Microsoft’s DirectInput libraries. This is a library geared towards input via a wide-variety of tactile devices which makes programming for specialized hardware and virtual worlds easier.

3.3 CAS Specifications

The overall structure of this experiment is the comparison of several different CASs, each of which differs from another only in the type of alert. In this section we design the CASs to be compared, starting with the common feature.

3.3.1 Alert Criteria

Of the three types of alert criteria discussed, it seems clear that fixed criteria are too simplistic and conditional criteria are unproven. A TTC criterion is the obvious choice. The question still remains whether to use a simple TTC of 4 seconds which has been proven to be effective, or whether to use a potentially better modified criterion by using a TTC plus a modifying factor based on speed as Hirst & Graham (1995) suggest. We choose a simple TTC of 4 seconds for two main reasons.

Using a criterion that has been repeatedly tested to be effective will give us the ability to compare our results to bigger ad more elaborate studies helping to validate the results. Using an untested criterion would add further complications, as it is impossible to predict whether this will be an effective criterion without doing an empirical study. Since
this study is not focused on CAS alert criteria, validating an untested criterion is beyond our scope.

3.3.2 Types of Alerts

- **Visual Alert** – There are two choices to be made here. We choose an abstract alert over a pictorial alert, since it has been shown that pictorial alerts can be distracting and actually increase response times. Similarly we choose a heads up display over a dashboard display since this has shown to result in faster response times. It seems clear that for an abstract visual alert, a heads–up display is clearly likely to give better results than a dashboard display which would require monitoring of an area other than the visual scene. The alert we use is a red rectangle superimposed on the lowest fifth of the scene (see the sample scene with alert given in the next section). The rectangle blinks at a frequency of 6Hz to heighten the sense of urgency it imparts.

- **Visual Continuous Display** – Hirst & Graham (1995) suggest the use of a continuous visual display of headway together with alerts. However, their own study does not imply his, suggesting instead that a continuous visual display offers no benefits (at least when used by itself). Their hypothesis has not been validated and the use of a continuous visual display could add to the visual workload of the driver, negatively affecting his performance and driving behavior. In addition, the use of a continuous visual display could hide the effect of the continuous auditory display being investigated. We elect not to go with continuous visual display of information.

- **Abstract Auditory Alert (non–spatialized)** – The auditory alert should serve to grab the attention of the subject as effectively as possible. Patterson (1982) developed several guidelines for the design of an effective auditory alert. Although he proposed these without empirical data, most of his suggestions have been borne out by later work. He proposed the following characteristics.
  - Should be presented at a specific sound pressure level as determined by future testing.
  - The basic pulse should last from 100–300 milliseconds.
  - The sound pulse should be contained within an amplitude envelope with short onset and offset times.
  - The pulse should contain a fundamental frequency and several harmonics.
  - The basic pulse should be repeated several times with a varying pitch, amplitude and time period between successive pulses.

These suggestions are very vague and were later expanded upon by Edworthy, Loxley and Dennis (1991). They carried out several empirical studies using Patterson’s guidelines and elaborated on the effect of several parameters on the perceived urgency of an alert. Their findings are summarized in Table 2 below taken from their work.
Parameter Effect on perceived urgency

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on perceived urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Frequency</td>
<td>Higher frequencies are seen as more urgent.</td>
</tr>
<tr>
<td>Amplitude Envelope</td>
<td>Shorter onset and offset times are seen as more urgent.</td>
</tr>
<tr>
<td>Distribution of frequencies</td>
<td>Irregular and unpredictable distributions have a higher perceived urgency.</td>
</tr>
<tr>
<td>Speed/time between pulses</td>
<td>Faster alerts, which have less time between successive pulses, are more urgent.</td>
</tr>
<tr>
<td>Rhythm</td>
<td>An irregular rhythm is perceived to be more urgent.</td>
</tr>
<tr>
<td>Number of pulses</td>
<td>More pulses make an alert seem to be more urgent.</td>
</tr>
<tr>
<td>Tonal Structure</td>
<td>Atonal alerts have a higher urgency.</td>
</tr>
<tr>
<td>Pulse amplitude</td>
<td>Higher amplitudes are seen as more urgent.</td>
</tr>
</tbody>
</table>

Table 2: Effect of various characteristics of an auditory alert on perceived urgency

The alert we used is based on these results. It contains a basic atonal pulse, repeated four times in quick succession. Each pulse lasts for about .1 second and is modulated by a pulse envelope with a short offset and onset. Figure X shows the waveform of the auditory alert used along with the modulating envelope.

- Abstract Auditory Alert (spatialized) – This alert is identical to the one above except that it has been passed through spatializing filters such that it appears to be located at the virtual position of the vehicle in front. Since the alert has some temporal extent, during its brief existence it will appear to move with the vehicle in front. This effect may or may not be noticeable.
Waveform of Auditory Alert

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09

Time

Figure 5: Waveform of basic pulse of auditory alert. Dashed line is the modulating envelope.

- Auditory Continuous Display (spatialized) – This alert seeks to alert the driver earlier but in a less intrusive way. For this alert we use a sound which mimics the natural sound of a car and is located at the position of the car in front. We use a fixed TTC of 5 seconds or a headway of 1.5 seconds, whichever comes first. In theory this should give the driver ample time to react once he has acknowledged the alert.

This alert starts off at a fixed level above the minimum sound pressure level detectable by the user. This is tested by a simple program which runs before any of the scenarios do. The level is low enough so that it should not cause any annoyance to the driver and has the advantage of being familiar to the driver.

3.4 Driving Simulator

The driving simulator has a complicated main objective. It should be simple enough that it can be developed quickly and results are reproducible and valid. Psychophysical results from simulations have often been accused of being nothing but side effects of features specific to the simulation. A valid experiment will eliminate these specific features while retaining the essential features of the system being simulated. This
simulation should therefore be as simple as possible, while reproducing all of the characteristics that are essential to the experiment.

For this experiment, it was decided that the simulator should have at least the following features:

- Shapes and colours of cars and any other obstacles
- A well-delineated two-lane road
- A simple complete driving route
- A constant flow of traffic to interact with
- Ability to completely measure all driver responses (pressure on brake and gas pedals and degree of steering) as well as other useful quantities (position, speed, proximity from nearest car etc.)
- A relatively accurate feel to the braking / acceleration and steering mechanisms, comparable to a regular car
- Sufficient scenery and accurate linear dimensions so that an accurate perspective is easily obtained
- A sufficiently high scene refresh rate so that movement seems smooth (about 20 times per second).

A virtual driving environment was designed with these goals in mind. The scene consisted of a 3 kilometer two-lane road, with traffic going in both directions. Each lane is 2 meters wide and the delineating lines are 8 centimeters wide. Houses are spaced out on either side of the road to establish perspective. Figure 6 shows the layout of a segment of the road. Traffic consisted of red cars on the left (approaching driver) traveling at 50 miles per hour and yellow vans on the right (same-direction as subject) traveling at 40 miles per hour. Traffic was generated randomly at the start of the simulation and then during the duration of the simulation. Approaching cars were frequent enough and fast enough that overtaking was not easy to accomplish. Appendix A contains openGL code for the static scenery as well as the vehicles. Appendix B gives details of the traffic generation.

We give three scene shots showing the simulator in common situations. The first shows the scene the subject sees at the start. The subject starts off on the shoulder. The next shot shows a scene while driving. The final shot shows a visual alert superimposed on the driver’s scene. This rectangle is bright red and blinks with a 3 times a second, persisting on the screen for 150ms each time. Because the grayscale equivalents of a the van color and the road color are similar, the vans are invisible and had to be outlined for clarity. The blurred text on the scene is a digital readout of the vehicle’s speed.
Figure 6: Layout of Driving Route
Figure 7a: Scene at start of Simulation

Figure 7b: Scene while driving. Leading vehicle outlined for clarity.
Figure 7c: Scene showing a visual alert. Leading Vehicle outlined for clarity.
4 Experimental Validation

4.1 Experimental Methodology

12 volunteers agreed to perform the experiment. Each of them was given the following series of instructions.

The experimental setup is a driving simulator. The simulated environment is a two lane road with traffic going in both directions. Your initial position is on the shoulder. You can control the speed of the car with the gas and brake pedals and the steering with the left and right arrow keys on the keyboard.

Your task is to drive along this road in the same direction as you are initially facing until you reach the end of the driving route. The simulation will terminate automatically when you pass the end. You will first have to merge onto the road. Please observe the following rules.

- There is no speed limit or time limit. You are to drive as fast as you would normally, at a speed at which you find comfortable.
- Please do not overtake onto the shoulder. If you want to overtake, you should overtake using the other lane of the road.
- If you crash into a house or another vehicle, please continue as normal.
- There is no need to use the left and right indicators to signal turning.
- Side mirrors are not necessary as you can assume that vehicles behind you will stop for you.

Each subject had to perform the same task once or twice as "trial" runs until they indicated they were comfortable with the setup. These "trial" runs did not have any alerts, but were otherwise identical to other runs. After they indicated that they were comfortable with the setup, and in particular with the steering mechanism, they were asked to perform 8 more runs. Each of these 8 runs used a different collision alert as specified in the following table. Each alert consisted of a pair of a present or non-present visual alert together with a present or non-present auditory alert (three different types). This led to a total of 8 possibilities.

After performing all 8 tasks, each subject was given a questionnaire to fill out. This survey is given in Appendix C.
4.2 Results

Preliminary results are given in the following table. There is a large amount of data and a lot of further processing and analysis of the data remains to be done.

<table>
<thead>
<tr>
<th>Table 3: Different Collision Alerts used</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual Alert?</strong></td>
</tr>
<tr>
<td>1 Yes</td>
</tr>
<tr>
<td>2 No</td>
</tr>
<tr>
<td>3 Yes</td>
</tr>
<tr>
<td>4 No</td>
</tr>
<tr>
<td>5 Yes</td>
</tr>
<tr>
<td>6 No</td>
</tr>
<tr>
<td>7 Yes</td>
</tr>
<tr>
<td>8 No</td>
</tr>
</tbody>
</table>

Table 4: Effects of Different Alerts on Average Speed

<table>
<thead>
<tr>
<th>Type of Alert</th>
<th>Average Speed (miles/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.6</td>
</tr>
<tr>
<td>2</td>
<td>17.4</td>
</tr>
<tr>
<td>3</td>
<td>17.6</td>
</tr>
<tr>
<td>4</td>
<td>17.3</td>
</tr>
<tr>
<td>5</td>
<td>18.6</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>17.9</td>
</tr>
<tr>
<td>8</td>
<td>18.7</td>
</tr>
</tbody>
</table>
5 Conclusion

This study has done preliminary work on the use of spatial audio alerts as well as performing a free-form experiment to determine the effect of these and other recommended alerts on driving behaviour. The results have been difficult to analyze because of the very free-form nature of the results. However, preliminary processing of the results indicates that although alerts may help to make the driver aware of his surroundings, they may help him lapse into a sense of added safety, causing him to actually drive less safely. This effect may overshadow any benefits provided.
References


Appendix A – OpenGL Specifications for visual scene

**Ground**
The first quad is the ground. The other three quads are the lines on the road.

```plaintext
shape = QUADS
color3 = 0.6, 0.6, 0.6
normal = 0.0, 1.0, 0.0
vertex = -1500.0, 0.0, -1500.0
vertex = -1500.0, 0.0, 1500.0
vertex = 1500.0, 0.0, -1500.0
vertex = 1500.0, 0.0, 1500.0

color3 = 1, 1 , 1
normal = 0.0, 1.0, 0.0
vertex = -4.04, 0.04, -1500.0
vertex = -4.04, 0.04, 1500.0
vertex = -3.96, 0.04, 1500.0
vertex = -3.96, 0.04, -1500.0

color3 = 1, 1 , 0
normal = 0.0, 1.0, 0.0
vertex = -6.04, 0.04, -1500.0
vertex = -6.04, 0.04, 1500.0
vertex = -5.96, 0.04, 1500.0
vertex = -5.96, 0.04, -1500.0

color3 = 1, 1 , 1
normal = 0.0, 1.0, 0.0
vertex = -8.04, 0.04, -1500.0
vertex = -8.04, 0.04, 1500.0
vertex = -7.96, 0.04, 1500.0
vertex = -7.96, 0.04, -1500.0
```

**House**
The last two quads are the doors. The two triangles are the corners of the roof.

```plaintext
shape = QUADS
color3 = 0.7, 0.7, 0.0
normal = 0.0, 0.0, 1.0
vertex = 0.0, 0.0, 0.0
vertex = 10.0, 0.0, 0.0
vertex = 10.0, 5.0, 0.0
vertex = 0.0, 5.0, 0.0
```
normal = 1.0, 0.0, 0.0
vertex = 10.0, 0.0, 0.0
vertex = 10.0, 0.0, -4.0
vertex = 10.0, 5.0, -4.0
vertex = 10.0, 5.0, 0.0

normal = 0.0, 0.0, -4.0
vertex = 10.0, 0.0, -4.0
vertex = 0.0, 0.0, -4.0
vertex = 0.0, 5.0, -4.0
vertex = 10.0, 5.0, -4.0

normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.0, -4.0
vertex = 0.0, 0.0, 0.0
vertex = 0.0, 5.0, 0.0
vertex = 0.0, 5.0, -4.0

shape = TRIANGLES
vertex = 0.0, 5.0, 0.0
vertex = 10.0, 5.0, 0.0
vertex = 5, 7, 0.0
vertex = 10.0, 5.0, -4.0
vertex = 0.0, 5.0, -4.0
vertex = 5, 7, -4.0

shape = QUADS
color3 = 0.9, 0.9, 0.9
normal = -0.25, 0.5, 0.0
vertex = 0.0, 5.0, -4.0
vertex = 0.0, 5.0, 0.0
vertex = 5, 7, 0.0
vertex = 5, 7, -4.0

normal = 0.25, 0.5, 0.0
vertex = 10.0, 5.0, 0.0
vertex = 10.0, 5.0, -4.0
vertex = 5, 7, -4.0
vertex = 5, 7, 0.0

shape = QUADS
color3 = 1, 1, 1
normal = 1.0, 0.0, 0.0
vertex = 10.01, 0.0, -1.60
vertex = 10.01, 0.0, -2.40
vertex = 10.01, 2.0, -2.40
vertex = 10.01, 2.0, -1.60
color3 = 1, 1, 1
normal = -1.0, 0.0, 0.0
vertex = -0.01, 0.0, -2.40
vertex = -0.01, 0.0, -1.60
vertex = -0.01, 2.0, -1.60
vertex = -0.01, 2.0, -2.40

Car
Lines preceded by "//" are comments indicating what the shapes represent.

// front bumper
shape = QUADS
color3 = 1.0, 0.0, 0.4
normal = 0.0, 0.0, 1.0
vertex = 0.0, 0.02, 0.0
vertex = 0.7, 0.02, 0.0
vertex = 0.7, 0.3, 0.0
vertex = 0.0, 0.3, 0.0

// right-rear panel
normal = 1.0, 0.0, 0.0
vertex = 0.7, 0.02, -0.3
vertex = 0.7, 0.5, -1.0
vertex = 0.7, 0.5, -0.3

// right-front lower panel
normal = 1.0, 0.0, 0.0
vertex = 0.7, 0.02, 0.0
vertex = 0.7, 0.02, -0.3
vertex = 0.7, 0.3, -0.3
vertex = 0.7, 0.3, 0.0

// right-front upper panel/window
shape = TRIANGLES
color3 = 0.0, 0.0, 0.2
normal = 1.0, 0.0, 0.0
vertex = 0.7, 0.3, 0.0
vertex = 0.7, 0.3, -0.3
vertex = 0.7, 0.5, -0.3

// rear
shape = QUADS
color3 = 1.0, 0.0, 0.4
normal = 0.0, 0.0, -1.0
vertex = 0.7, 0.02, -1.0
vertex = 0.0, 0.02, -1.0
vertex = 0.0, 0.5, -1.0
vertex = 0.7, 0.5, -1.0

// left-back panel
normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.02, -1.0
vertex = 0.0, 0.02, -0.3
vertex = 0.0, 0.5, -0.3
vertex = 0.0, 0.5, -1.0

// left-front lower panel
normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.02, -1.0
vertex = 0.0, 0.02, 0.0
vertex = 0.0, 0.3, 0.0
vertex = 0.0, 0.3, -0.3

// right-front upper panel/window
shape = TRIANGLES
color3 = 0.0, 0.0, 0.2
normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.3, -0.3
vertex = 0.0, 0.3, 0.0
vertex = 0.0, 0.5, -0.3

// roof
shape = QUADS
color3 = 1.0, 0.0, 0.4
normal = 0.0, -1.0, 0.0
vertex = 0.0, 0.5, -0.3
vertex = 0.0, 0.5, -1.0
vertex = 0.7, 0.5, -1.0
vertex = 0.7, 0.5, -0.3

// windshield
color3 = 0.0, 0.0, 0.2
normal = 0.0, 0.3, 0.1
vertex = 0.0, 0.3, 0.0
vertex = 0.7, 0.3, 0.0
vertex = 0.7, 0.5, -0.3
vertex = 0.0, 0.5, -0.3
Van
Lines preceded by "//" are comments indicating what the shapes represent.

// front bumper
shape = QUADS
color3 = 1.0, 1.0, 0.0
normal = 0.0, 0.0, 1.0
vertex = 0.0, 0.02, 0.0
vertex = 0.7, 0.02, 0.0
vertex = 0.7, 0.5, 0.0
vertex = 0.0, 0.5, 0.0

// right–rear panel
color3 = 0.8, 0.8, 0.0
normal = 1.0, 0.0, 0.0
vertex = 0.7, 0.02, −0.3
vertex = 0.7, 0.02, −1.2
vertex = 0.7, 0.8, −1.2
vertex = 0.7, 0.8, −0.3

// right–front lower panel
normal = 1.0, 0.0, 0.0
vertex = 0.7, 0.02, 0.0
vertex = 0.7, 0.02, −0.3
vertex = 0.7, 0.5, −0.3
vertex = 0.7, 0.5, 0.0

// right–front upper panel/window
shape = TRIANGLES
color3 = 0.0, 0.0, 0.2
normal = 1.0, 0.0, 0.0
vertex = 0.7, 0.5, 0.0
vertex = 0.7, 0.5, −0.3
vertex = 0.7, 0.8, −0.3

// rear
shape = QUADS
color3 = 1.0, 1.0, 0.0
normal = 0.0, 0.0, −1.0
vertex = 0.7, 0.02, −1.2
vertex = 0.0, 0.02, −1.2
vertex = 0.0, 0.8, −1.2
vertex = 0.7, 0.8, −1.2

// left–back panel
color3 = 0.8, 0.8, 0.0
normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.02, -1.2
vertex = 0.0, 0.02, -0.3
vertex = 0.0, 0.8, -0.3
vertex = 0.0, 0.8, -1.2

// left-front lower panel
normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.02, -0.3
vertex = 0.0, 0.02, 0.0
vertex = 0.0, 0.5, 0.0
vertex = 0.0, 0.5, -0.3

// right-front upper panel/window
shape = TRIANGLES
color3 = 0.0, 0.0, 0.2
normal = -1.0, 0.0, 0.0
vertex = 0.0, 0.5, -0.3
vertex = 0.0, 0.5, 0.0
vertex = 0.0, 0.8, -0.3

// roof
shape = QUADS
color3 = 0.8, 0.8, 0.0
normal = 0.0, -1.0, 0.0
vertex = 0.0, 0.8, -0.3
vertex = 0.0, 0.8, -1.2
vertex = 0.7, 0.8, -1.2
vertex = 0.7, 0.8, -0.3

// windshield
color3 = 0.0, 0.0, 0.2
normal = 0.0, 0.3, 0.3
vertex = 0.0, 0.5, 0.0
vertex = 0.7, 0.5, 0.0
vertex = 0.7, 0.8, -0.3
vertex = 0.0, 0.8, -0.3
Appendix B – Pseudo-code for generation of Traffic

The scene is initialized with cars and vans already on the road

for i=every 100 meters
    { NewCar at a random point between i and i+100 meters
      NewVan at a random point between i and i+100 meters
    }

The following routine is run every time the scene is updated to ensure that there is always a constant stream of cars and vans. This creates on average one new car every 8 seconds and one new van every 6 seconds.

If (2 seconds has elapsed since last check) 
    { if (a random integer is divisible by 4) 
        { NewCar at end of driving route (since they are approaching) 
        }
    }
    if (a different random integer is divisible by 3) 
    { NewVan at start of driving route
    }
    Update time checked
}
Appendix C – Post–Experiment Questionnaire

Please answer the following questions with a number from 1 to 5 where 1 represents a strong agreement and 5 is a strong disagreement.

1 – Strongly Agree 5 – Strongly Disagree

1) The information conveyed by the collision alert was useful to me.

2) The information conveyed by the collision alert helped me drive more safely.

3) The presence of the collision alert did not negatively affect my driving.

4) The collision alerts seemed to be unpredictable and/or unreliable so I largely ignored them.

5) I was able to more easily avoid potentially dangerous situations because of the collision alerts.

6) The alerts occurred too early, well before I was intending to take action.

7) The alerts occurred too late, so I did not have time to use the information provided.

8) The blinking–red–rectangle alert was
   – easy to understand/interpret as a warning.
   – annoying/distracting
   – effective as a warning
7) The triple beep alert was
- easy to understand/interpret as a warning.
- annoying/distracting
- effective as a warning

8) The simulated automobile sound
- easy to understand/interpret as a warning.
- annoying/distracting
- effective as a warning
- I did not hear/interpret the simulated automobile sound

9) Rank the following combinations in terms of the order of effectiveness as warning signals.
1 – Most effective  6 – least effective
Red–blinking–rectangle alone –
Red–blinking–rectangle and Triple–beep warning –
Red–blinking–rectangle and Automobile sound –
No alert –
Triple–beep warning alone –
Automobile sound alone –

10) The alerts enabled me to drive faster / closer to the car in front than I would normally.
1 – agree strongly  5 – disagree strongly

11) After the trial run, the simulator modelled the feel of a real driving situation.
1 – Agree strongly  5 – disagree strongly

12) What 2 aspects of the simulator were most functionally different from a real driving situation (excluding visual realism of the surroundings)?

i) 

ii)
13) There were two types of triple-beep alerts – one at the location of the car in front and one at a constant location. Could you tell the difference?
Yes/No/Not Sure –

14) If yes, this effect helped gauge the urgency of the alert.
1 – Agree strongly 5 – disagree strongly.

15) Do you have any other comments about the experiment that you think would be useful?