CHAPTER 1: LITERATURE REVIEW

Introduction

This thesis is a proof-of-concept study that aims to reduce the high incidences of rear end crashes that contribute to increasing high numbers of overall crash rates in the U.S. today. The concept is a flashing rear strobe light, which serves as a warning signal to drivers too close to the vehicle in front in car-following situations. Strobe lights have been used to successfully raise conspicuity of vehicles, and objects in many other transportation applications. This study was designed with the intention that if this signal was effective at positively affecting subjects' response times to an unexpected stopped vehicle in the roadway, the results of this study would provide the basis for seriously considering such a light in future development of rear signaling applications.

This literature review provides background information investigating rear end crash causation. Current countermeasures are reviewed, together with their effectiveness and associated research. In order to develop a new concept it is important that the principles of warning design be reviewed. These are presented together with associated research concerning the effectiveness of certain lighting configurations. Literature concerning the effectiveness of strobes at enhancing conspicuity in other transportation research areas is documented. Other considerations in developing a warning signal such as timing and impact of varied reaction times on activation criteria are also presented. Approaches to investigation of unexpected emergency braking are also reviewed concerning issues of testing environment, obstruction presentation, and measures of effectiveness.

Crash Causation

Reducing crashes has been a focus of human factors for many years. In 1997 alone more than 6.7 million motor vehicle crashes on U.S. highways were reported to the police - one every 5 seconds. On average a person was injured in these crashes every 9 seconds and someone killed every 13 minutes (NHTSA, 1998). One of the most extensive studies to determine the cause of these crashes was the Indiana Tri-Level Study by Treat, Trumbas, McDonald, Shinar, Hume, Mayer, Stansifer, and Catellan (1979). The study determined that driver errors were a definite or probable cause (or at least a severity-increasing factor) in 93% of crashes. The types of human errors that cause crashes were identified as recognition, decision, and performance errors. According to Treat et al. (1979), recognition errors were responsible for 56% of all crashes in the Tri Level study. These types of errors refer to those situations where a conscious driver does not properly perceive, comprehend, or react to a conflict requiring a driver response. The types of recognition errors include inattention, distraction, and "looked but did not see." Decision errors constituted a probable cause of 52% of the Tri-Level crashes. These errors refer to situations where the driver selected an improper course of action to avoid a crash. Sample categories include false assumptions and tailgating. Finally, performance errors are conflicts in which the driver properly comprehends and selects an appropriate action, but makes an error in executing that action (e.g., oversteering, panic, or freezing). These were apparent in only 11% of the Tri-Level crashes. Out of three categories identified by Treat et al. (1979), human error was identified as the major factor in crash causation.

Rear End Crashes

Rear end crashes are one of the largest crash and injury contributors to this road traffic problem and these types of crashes have continued to increase over the years. According to the National Highway Traffic Safety Administration (NHTSA, 1998), in 1997 there were 1.9 million rear-end crashes (28.4 percent of all crashes) compared to approximately 1.5 million rear end crashes (25 percent of all crashes) in 1992 (NHTSA, 1993). Rear end crashes are also estimated to cause one third of crashes responsible for traffic delays and incur about 21% of total crash costs (Wang et al., 1996).

Numerous researchers agree that about two-thirds of all rear end crashes are Lead Vehicle Stationary (LVS) crashes as opposed to Lead Vehicle Moving (LVM) crashes (Horowitz, 1994; Knipling, Hendricks, Koziol, Allen, Tijerina, and Wilson, 1992; Mortimer, 1981). LVS crashes were also thought to be less severe but accounted for the most injuries, crashes, and fatalities. Knipling et al. (1992) found that the most common pre-crash vehicle maneuver for the striking vehicle was simply "going straight" (84 % of cases).

The pattern of causal factors identified in the Tri-Level study (Treat et al., 1979) is true for both LVS and LVM crash subtypes - especially LVS. As mentioned previously, out of three categories identified by Treat et al. (1979), human error was identified as the major factor in crash causation. The other two categories included vehicle and highway design. However, Dingus, Jahns, Horowitz, and Knipling (1998) point out that these categories of causation all interact and enforce one another. As a result, preventative measures should seek to enhance the safety of vehicles (e.g., collision warning systems) and/or the environment (e.g., intelligent signaling) to compensate for driver error. Enhancing these factors would effectively reduce driver error through more positive interaction. However, the types of driver error need to be fully understood before design recommendations can be made to alleviate these crash causes.

Driver Error

The most common category of driver error associated with rear end collisions is inattention to the driving task. A second overlapping factor is following too closely. One or both of these factors are present in approximately 90% of rear end crashes (Knipling et al., 1993). What follows is a breakdown of the apparent causes of driver error as identified in the literature. These include perceptual factors, short headways, and inattentive behavior.

Perceptual factors. There is considerable literature supporting the theory that complex perceptual factors contribute to a driver's failure to see the vehicle ahead prior to a rear end crash event (Mortimer, 1988). Lee (1976) analyzed rear end crashes in terms of perception and ascertained that drivers are predictive in their behavior when driving. They plan what to do next based on the dynamics of the optic array.

Lee (1976) divides the task of approaching slower moving, stopping, or stationary vehicles into three consecutive stages:

1) Detection of closing in
2) Initiation of braking
3) Regulation of braking force to avoid crash

The first stage (detecting of closing in) is performed using visual closure information. Rear lights support this first stage to a certain extent, but they do not support the second stage (initiation of braking). Lee (1976) had determined that in order for a driver to decide the initiation and urgency of braking, he/she must have information on closing rate. That is, the driver must anticipate the moment of impending collision known as time to collision. Time-to-collision (TTC) is defined by Cavallo and Laurent (1988) as "the time it will take to reach an obstacle," a crucial predictor in brake regulation. The equation used in TTC calculation is as follows:

$$\text{TTC (sec)} = \frac{\text{Inter-vehicle Distance or Headway (ft)}}{\text{Relative Speed or Closure rate (ft/sec).}} \qquad (1)$$

where:

Intervehicle Distance/Headway (ft) = the distance in feet between the lead vehicle and the following vehicle

Relative Speed/Closure rate (ft/sec) = the speed of the following vehicle minus the speed of the lead vehicle.

The information contained in this equation is essential to determine the need to start braking, as well as the magnitude of the force required to avoid a potential crash (stage 3). Drivers receive feedback concerning the adequacy of their braking from the rate of change of the TTC. Based on driver behavior and capabilities, the current literature presents problems associated with the first and second stages. In terms of stage one, detecting closing rate, drivers are accurate and sensitive at judging whether the gap between themselves and the car in front is opening or closing (the direction of relative velocity), but are unable to judge their own velocity in relation to the vehicle ahead (relative velocity) (Janssen, Michon, and Harvey, 1976; Mortimer, 1990). As a result, the detection of closing rate on the vehicle in front can be problematic. Unless the relative velocity between two vehicles is quite high, drivers will simply rely on changes in headway or visual cues for determining the speed they should adopt when following another vehicle. With regard to Lee's second stage, initiation of braking, headway distances adopted by drivers tend typically to be too short for the speed of travel to avoid a rear end crash. Time-to-collision information is critical to drivers when determining initiation and subsequent regulation of braking. The TTC adopted when following at short headway distances such as these is deficient, increasing the probability of a rear end crash.

Short headways. Headway is defined as:

> ...the elapsed time between the front of the lead vehicle passing a point on the roadway and the front of the following vehicle passing the same point. (Evans, 1991, p. 313).

This issue is related to perceptual factors, but several studies and research discussions in the area cite the problem of following at short headway distances as a primary cause of rear end crashes (Carney, 1996; Fancher, Ervin, Sayer, Hagan, Bogard, Bareket, Mefford, and Haugen, 1998; Wasielewski, 1979). Wasielewski (1979) calculated that the average following distance for most drivers is 1.32 seconds with a standard deviation of 0.52 seconds. Fancher et al. (1998) suggests an estimate of 0.65 second for 10 percent of drivers in the United States. Many drivers would be unable to stop successfully in these circumstances. This is due to the resulting short TTC that would occur if the lead car were to brake sharply.

Most official driver instructions and recommendations suggest a headway or gap of two to three seconds to the car ahead. However, the minimum time gap a driver needs for reaction time and braking time varies with relative velocity (i.e., their speed and the speed of the car ahead). Using a single headway distance independent of speed and variability in reaction time is not safe. Data from Fancher et al. (1998) demonstrate that speeds over about 90km/h require large variation in time gaps from 0.3 to 3 seconds (the most likely gap being 0.8 seconds). He concluded that a time gap of five seconds at high speeds would be safe when encountering a stationary or slow moving vehicle.

Liebermann, Ben-David, Schweitzer, Apter, and Parush (1995), in a study concerning emergency braking, suggest that braking was both a controlled and automatic response. Liebermann et al. (1995) suggest that the onset of brake lights triggers an automatic brake response unlike Lee's (1976) model of planned response. The modulation of this braking response according to Liebermann et al. (1995) is influenced by the optic expansion of the lead vehicle. They also found that drivers reacted faster at shorter following distances.

Evans (1991) provides a widely accepted explanation about close following distances/headways. According to Evans, a largely static impression is created if coupled cars are heading in the same direction at identical speeds. This static visual image results in a lower awareness and concern about speed. However, if the lead vehicle were to suddenly slow down, the ensuing dynamic behavior is speed dependent (as well as the amount of energy dispersed in the event of a crash).

Evans (1991) goes on to suggest that driver comfort at maintaining a close headway may have been learned from repeated experience. This experience teaches drivers that it is safe to maintain short headway distances as many car-following situations result in no adverse consequences. Drivers learn that vehicles in front rarely slow down at a rapid rate. Evans speculates that based on these issues, maintaining close headway distance becomes habit forming and is largely not a conscious decision.

Unfortunately, the faster the closing velocity in the event of a car slowing or stopping, the less time a driver has to detect, react, and brake. Collision risk is greater the narrower the visible width of the vehicle in front (as enhanced by standard brake lights) due to the difficulties people have in detecting closing rate (Janssen et al., 1976). Not only are people voluntarily developing risky driving behavior, but they also have limited success at estimating distance, closure rate, and speed change of the car ahead. Somehow the guesswork needs to be taken out of estimating these factors so that the driver knows the appropriate point to initiate and regulate braking. According to Moore and Rumar (1999), elimination of risky driving behavior can only be adopted through experience and training, but they also agree that rear lighting systems need to be improved.

Inattentive behavior. The driver of a vehicle must attend to many visual and auditory signals, often at the same time, in a multi-task driving environment. There are two distinct modes of allocating attention while perceiving the visual environment: serial and parallel processing. Scanning the busy outside world and then switching to collecting information from the instrument panel is one example of forced serial processing. Most visual tasks require this type of processing. Parallel processing can also occur whereby visual and auditory information are processed at the same time, for example, listening to a radio report while scanning the roadway.

A driver's attention to serial processing of visual stimuli has been described in the literature as similar to a "spotlight" (Dingus et al., 1998). Only areas that are illuminated are attended to at any one time, forcing the driver to initiate a scanning behavior to collect information in the environment (not all of this information can be captured in foveal vision). However, serial scanning behavior can lead to the driver losing track of the last time information was sampled. This situation becomes more complex as this information also has to be prioritized in terms of importance. If the driver is overloaded (as in the case of busy traffic situations), less critical information receives less attention. This finding has had practical implications for display design where visual displays have been grouped close to the primary visual task (in cases of high stress such as crash avoidance). Conversely, too little stimulation, such as a freeway with no traffic, results in the driver becoming very comfortable in his/her ability to perform the driving task. Day -dreaming can result which also diverts the driver’s attention away from driving. Either of these situations (cognitive overload or underload) would result in increased probability of a collision (Stokes, Wickens, and Kite, 1990).

Peripheral vision can also affect attention. According to Dingus et al. (1998), parallel processing of information occurs when a driver relies on motion cues from peripheral vision to maintain lane position. Since visual acuity decreases further away from the fovea, this part of the retina is largely used to detect motion and luminosity. The authors suggest that displays that utilize a flashing light or streak of light across a windscreen may orient the driver much better than any cluster of in-vehicle displays.

One final consideration is that attention to the driving task can degrade as experience and skill increases. As a result, drivers attend more to non-traffic targets (e.g., speedometer, sight seeing, in-car accessories), some of which may or may not be necessary (Summala, Lamble, and Laasko, 1998). Summala et al. (1998) recently performed a study that examined the detection of brake lights while the drivers were distracted by displays that were placed at various positions on the dashboard. Their results supported a substantial delay in brake reaction times as a result of failing to see conventional brake lights. This led the authors to conclude that in daylight brake lights help little or not at all in the detection of lead car deceleration by a distracted driver.

Conventional brake light design does not seem to have taken attentional factors into account. As demonstrated by Summala et al. (1998), attendance to in-vehicle targets can lead to failure in detecting brake lights of the lead vehicle. This is probably impacted by insufficient resolution in peripheral vision of drivers. Regan, Hamstra, and Kaushal (1992) point out that viewing objects in the periphery could affect estimation of TTC (although little has been done to support this theory). Visual sensitivity does, however, degrade steeply with increasing eccentricity of view (Regan and Beverley, 1983). Regan et al. (1992) further suggest that due to this decrease in visual sensitivity, the just-detectable closing speed is considerably higher in peripheral than in central vision.

<u>Countermeasures</u>

The first brake lights appeared in the US in 1905 and were implemented in all states by 1928. Current brake lamp luminous intensity specifications for the U.S. are between 80 and 300cd (different from European requirements of 40 to 100cd). Studies that compared U.S. and European requirements showed current U.S. intensity specifications are performing well by providing better reaction times than those of their European counterparts (Sivak, Flannagan, and Olson, 1987). However, studies such as Lee (1976), Summala et al. (1998), and Regan et al. (1992) have stressed the failure of conventional brake lights as attention-getting devices. Summala et al. (1998) suggest that lack of attention is due to the combination of insufficient resolution in the periphery and attendance to other tasks which may or may not be related to driving. These two factors result in the driver's inability to detect the onset of these lights among other lights in the environment. A steady increase in rear end crashes has further prompted transportation researchers to improve safety by upgrading the rear signaling system. After all, rear signals were developed to improve the uncertainty of the traffic scene presented to road users. Improving rear signaling could potentially reduce the occurrence of rear end crashes, as well as other types of crashes, such as lane changes, merging, left and right turns in intersections, U-turns, and backing, albeit to a lesser extent (Moore and Rumar, 1999).

Rear signaling improvements. Many design interventions have been conceptualized, tested, and in some cases implemented in an effort to reduce rear end crashes and the effects of driver error on crash rates. What follows is an overview of the more popular concepts.

Center high mounted stop lamps (CHMSL). A CHMSL is a red stop lamp mounted on the centerline of the rear of a vehicle at a position higher than that of the other two lamps mounted on the sides. The implementation of the CHMSL was brought about by the Motor Vehicle Safety Standard FMVSS-108 (Office of the Federal Register, 1985). This standard required that all new cars sold in the U.S. on or after September 1st, 1985 be equipped with this additional brake signal.

A good deal of research has supported the effectiveness of the CHMSL in reducing rear end crashes. Three reasons have been suggested for the effectiveness of the CHMSL. First, the CHMSL is a light source that is separated from presence lights and turn signals. Second, the triangular pattern created by the three brake lights results in greater attentional value. Third, the CHMSL is in the driver's line of sight (Sivak, Conn, and Olson, 1986; Theeuwes and Alferdinck, 1995; Sivak and Flannagan, 1993). Sivak et al. (1986) best demonstrated this third behavioral explanation by monitoring the eye fixations of subjects while they drove specific routes. These eye fixations tended to concentrate on the rear window of the lead car and not on the positioning of current low mounted brake lights. Sivak and Flannagan (1993) also demonstrated shorter driver reaction times resulting from brake lights that were located closer to eye fixations during driving.

Initial predictions were for a reduction of as much as 900,000 rear end collisions, as well as a reduction in the severity of collisions (Digges, Nicholson, and Rouse, 1985). Preliminary field studies showed a potential reduction of 50 to 60% (Malone, Kirkpatrick, Kohl, and Baker, 1978; Reilly, Kurke, and Buckenmaier, 1980). However, more recent research suggests that the reduction of rear end crashes is much lower than first predicted. A recent long-term study by Kahane and Hertz (1998) presented more moderate estimations of a 4.3 percent reduction in rear end crashes. The reasoning behind this reduction in the effectiveness of the CHMSL was thought to be due to the novelty effect, which had worn off over time. Nevertheless the CHMSL has proven to be the most cost-effective countermeasure to rear end crashes.

Flashing CHMSL. Flashing CHMSL's have been recommended as a more effective rear warning signal. Recall that studies conducted by researchers such as Sivak et al. (1986) also suggest that the eyes tend to concentrate on the rear window as opposed to the standard low mounted brake lights. This would make a center mounted position a perfect location for a flashing CHMSL to attract the attention of distracted drivers (Horowitz, 1994). Horowitz (1994) also suggests that changes be made to the intensity of the current CHMSL to enhance conspicuity further. He also proposes changing the intensity of the CHMSL as a function of ambient light: higher in daytime and lower at night.

There are also two main methods by which this signal could be triggered:

1) A flashing signal to indicate that a vehicle is stopped. This suggestion was based on Horowitz (1994) who proposes the use of a flashing CHMSL in certain traffic scenarios. He based suggested improvements to rear lighting signals on accident statistics and human factors considerations to five traffic scenarios. For each scenario he proposed the use of a specific signal. For a stopped vehicle he proposes the use of a red flashing signal located in or around the current CHMSL.

2) A flashing CHMSL to indicate sharp decelerations. A flashing CHMSL has been proposed (as an imminent warning signal) which is activated by the Antilock Braking System (ABS) (Horowitz, 1994; Browne and Chin, 1991). Browne and Chin further suggest that these flashing CHMSLs would be distinguishable from indicator lights due to location, and also due to a proposed frequency of urgency set at 4 to 5 Hz, with equal on and off times as recommended for urgency signals (Van Cott and Kinkade, 1972). Researchers such as Voevodsky (1974) have suggested the importance of using a flashing signal to indicate sharp decelerations. Voevodsky (1974) used a flashing amber light center mounted like a CHMSL on the rear of hundreds of taxi cabs in San Francisco. This light was meant to communicate the deceleration rate of the taxi to vehicles that

followed. This light was initiated by the use of the brake pedal and pulsed in a controlled fashion at a rate, duty cycle, and intensity that varied exponentially as a function of deceleration. His study reportedly prevented 5.4 collisions per million miles, a 60.6 percent reduction in rear collision rates. Many others however argued that any type of flashing signal indicating rapid deceleration would add little value (Mortimer, 1981; Mortimer and Sturgis, 1974). Moore and Rumar (1999) suggest that there is little empirical data available to draw any conclusions about the effectiveness of any signal to indicate rapid deceleration.

Advanced Brake Light Device (ABLD) also known as an Advanced Brake Warning System (ABWS). An ABLD/ABWS system is a brake light that is triggered by rapid accelerator release, a typical behavior prior to hard braking. Onset of the ABWS provides an advanced indication that the brake is going to be applied to the following vehicle in car-following situations. This signal is thought to appear 0.2 to 0.3 seconds sooner than conventional lights. Shinar, Rotenberg, and Cohen (1997) demonstrated the benefits of an ABWS by performing a Monte-Carlo type simulation. This used a car-following scenario in which two vehicles are traveling at the same speed. The lead vehicle suddenly brakes, causing the car brakes to lock and the vehicle to skid to a stop. The results of this simulation showed great benefits. Driver alertness and headway interacted significantly with the ABWS system. Unalerted drivers avoided 64 percent of rear end crashes as opposed to 0 percent without the ABWS system, whereas alerted drivers avoided 100 percent of rear end crashes as opposed to 55 percent without the system. The system reached peak effectiveness at headways of 1.0 seconds. Furthermore, the ABWS system reduced crash severity as well as crash rates. The authors found that an alert driver using an ABWS can avoid all crashes, even when headways are reduced to 0.5 seconds. Unalerted drivers maintaining an intervehicle separation of 0.75 to 1.00 seconds had an average reduction in crash severity of over 3km per hour. The benefits of this system, however, were derived based on the following questionable assumptions: 1) at the moment of braking the two vehicles are traveling at the same speed, 2) the following driver is looking at the lead vehicle's brake lights at the time of their onset, and 3) the following driver's response is to brake as soon as he/she perceives the brake lights.

Although benefits of the system have been studied (Shinar et al., 1997), researchers cannot agree on whether there is a high frequency of such rapid accelerator releases. A high number of false alarms would result, undermining the potential effectiveness of any kind of alert system (Dingus, et al.,1998). Mortimer (1997) estimated that there are about 18 billion accelerator releases every day in the U.S. and about 6 billion brake applications. These estimations led Mortimer to conclude that even a small proportion of false alarms caused by such a signal would be a large number of irrelevant signals. Conversely, Olson (1989) suggests that rapid accelerator releases are rare events. Olson (1989) reported only 3.4 percent rapid accelerator releases out of all braking actions tested.

In-vehicle collision avoidance warning systems. In-vehicle warning devices are an alternative to rear signal enhancement. This type of device could potentially reduce the number of rear end crashes by meeting the same objectives as improving rear-signaling systems (i.e., improving perception, comprehension, and rear following behavior). The inherent difference in these approaches is that the following vehicle receives some kind of in-vehicle warning signal/device as opposed to an external signal attached to the vehicle ahead.

The development of an in-vehicle collision avoidance warning system has become possible due to advances in sensor technology. The purpose of these systems is to avoid accidents caused by detection failures by alerting the driver to potentially hazardous situations via an in-vehicle-warning signal. These systems often require a correct and immediate response for crash avoidance resulting in a reduction in the amount of response time available to the driver to avoid the hazard.

Headway detection/maintenance. The most promising example of a collision avoidance warning display that addresses the causes of rear end crashes is a headway detection/maintenance system. A headway detection (HD) system is a concept that has the potential to perform three functions. The first is to recommend an increase in headway distance. Second, if a driver maintains a safe headway a mild warning rather than a severe one could be initiated. Third, the same visual display can be used as part of a collision warning display (Horowitz and Dingus, 1992). It is envisioned that this system would have a range of about 300 feet and would monitor the separation and closing rate between two vehicles. Once a critical distance between the two vehicles is reached, the system would provide the driver with an in-vehicle warning. The system would dynamically reduce warning distance ranges as a function of speed of the following vehicle to avoid nuisance alarms.

The HD system only addresses rear-end crashes that are caused by inattention or short headway distances which, as noted earlier, are the prime causes of rear end crashes. It does not address other causal factors such as unsafe driving acts, poor judgement, false assumptions, and vehicle component failure. In the Indiana Tri-Level Study (Treat et al., 1979), recognition errors were cited in 79% of rear end crash cases. Only these cases would be addressed by a HD system.

According to Knipling et al. (1993), analytical modeling predicts that a theoretical HD system could effectively reduce rear end collisions attributed to inattention and short headway distances by 40-80%. Several field studies indicate that a headway system would be behaviorally effective as subjects tended to increase their headway on the advice of the system when an informative display was present (Dingus, McGehee, Manakkal, Jahns, Carney, and Hankey, 1997). This change in behavior could potentially raise their situational awareness of unsafe car-following and lead car behavior.

Implications for display design. The success of such a system would be heavily influenced by the format of an in-vehicle display. Evans (1991) estimated that a driver is involved in a car crash on average once every 25 years. In theory, a rear end collision warning is a rare occurrence as drivers are very successful at avoiding collisions of this nature. This factor has implications for display design. It can reduce the cognitive load experienced by the driver as more information than necessary at this crucial time can be dangerous. It is important that the warning display does not startle the driver or divert driver attention away from other hazardous circumstances. Furthermore, it is vital that the driver understands the purpose of the activation of such a warning light to ensure an appropriate response. Interpreting the appropriate response to an unknown signal shifts attention from action to the new unexpected stimulus. This cognitive shift would add to driver cognitive load, leading to stress, delay in action, and possibly an incorrect response. If these factors are not taken into account, an increase in crash risk would result from the implementation of any collision warning device (Dingus et al. 1998).

Dingus et al. (1998) discuss the problems inherent in designing displays that require foveal vision inside the vehicle. They suggest that this would divert attention away from the hazard to which the system is trying to alert the driver. The authors suggest that displays that utilize a flashing light or streak of light across a windscreen may orient the driver much better than any cluster of in-vehicle displays. False alarms that would also detract foveal vision are also thought to be detrimental to the safety of the driver. Head Up Display (HUD) technology is a possible display design that could present headway information without the problems of attentional demand imposed by in-vehicle displays. HUD technology does this by providing information such as headway distance in the driver's foveal field of view (Hirst and Graham, 1996).

Dingus et al. (1998) propose four concepts for the representation of warnings that could minimize false alarms while still providing relevant timely information:

- graded sequence of warnings
- parallel change in modality
- individualization of warnings
- headway only display

Dingus et al. (1997) performed three on-road studies to determine how behavior would change when using HUD displays of varying modality and representations similar to the ones listed above. Their results indicated provision of important, relevant information concerning safe headway did in fact improve driver following behavior by an average of 0.5 seconds. Visual warnings were found to be more effective than auditory warnings, but the authors suggested that auditory displays might be useful in situations where deceleration is required as opposed to headway distance maintenance.

Intelligent cruise control. Intelligent cruise control research has implications for this study, as the timing of braking intervention is one critical factor that needs to be resolved if the system is to be effective. According to Maretzke and Jacob (1992), market success of such systems is currently elusive due to weakness of sensor technology to discriminate hazardous obstacles from non-hazardous obstacles in the roadway, the high cost of such sensors and actuating equipment, and high incidences of false alarms. There are intelligent cruise control systems currently available. For example, the Japanese have distributed special distance warning devices for commercial vehicles that have been on the market since 1990. Further developments are currently underway in the U.K. and U.S. to develop systems based on microwave radar technology. Distance warnings can be part of the functions supplied by such intelligent systems, which rely on the driver to change their input in response to such warnings. Other systems automatically intervene by controlling the accelerator or brake to adapt the inter-vehicular distance (Maretzke and Jacob, 1992).

<u>Nuisance/False Alarms</u>

Unfortunately, the effectiveness of systems such as collision avoidance and intelligent cruise control has been questioned due to the potential for false alarms. Alarms could be erroneously triggered during heavy traffic situations and limitations of sensor technology which could mistakenly identify objects on the roadside as obstacles. False alarms such as these could potentially result in driver distrust of the system (Dingus et al., 1997; Dingus et al. 1998; Knipling et al. 1993; Maretzke and Jacob, 1992). According to Dingus et al. (1998), problems associated with false and nuisance alarms were demonstrated in the design of the first generation of traffic-collision alerting system (TCAS-I) for commercial aircraft. These systems had such a high nuisance alarm rate that pilots failed to trust the system's validity as an alerting device. This situation could be analogous to what might happen in the automotive crash-warning domain.

<u>Warning Design</u>

The purpose of implementing a new rear signal, such as a strobe, is to warn a driver of an imminent crash. Providing a visual warning to the driver would theoretically result in an increase in the amount of response time available to the driver to avoid the hazard. However, these systems require a correct and immediate response for crash avoidance, raising issues concerning detection and comprehension of a warning in this setting.

There has been little research relating to imminent warning signals, but some general principles can be inferred from knowledge of human sensory and perceptual processes. There are many recommendations in the literature concerning the design for good warning signals. Morgan, Chapanis, Lund, and Cook (1963) propose that a good universal warning device should meet the following requirements:

- It should break through and get the attention of a busy or bored operator.
- It should be obvious to him/her what is wrong or what action to take.
- It should not prevent his/her continued attention to other important duties if this is necessary.

Flashing signals. According to Nickerson, Baron, Collins, and Crothers (1968), a flashing light signal can be utilized in visual display systems in two ways: 1) the flash rate itself can be used as a visual coding dimension to transmit information (e.g., one flash per second can mean "slow down" and three flashes can mean "come to a stop."), or 2) the flash signal can be used to enhance conspicuity, therefore more effectively attracting the attention of observers to its presence. For example, a flashing red signal may indicate "look" as opposed to a steady red signal which may indicate "stop." These two capabilities suggest that a flashing light can satisfy two of the criteria for an effective warning design (Morgan et al., 1963). The challenge when using a flashing light, however, is to ensure the third of these criteria. The light should not detract driver attention away from the task of driving. This suggests that effects such as startle should be avoided, as the driver will not be able to perform the evasive maneuver as effectively if startled.

Flashing lights as a coding mechanism. Nickerson et al. (1968) found that the faster the flash rate, the shorter the time for recognition. Their recognition times averaged between 15.5 seconds for 0.27 Hz to about 6 seconds for 12 Hz. However, the authors suggest that flashing is poor at coding various information as observers, in order to determine the rate of flash, must observe several onset and offset times. The categories of usable flash rates that can be discriminated is also small (Cohen and Dinnerstein, 1958).

Attentional value of flashing lights. It is generally accepted in the human factors literature that flashing signals are more effective at attracting the attention of observers than steady signals (Holmes, 1971; Morgan et al., 1963; Nickerson et al., 1968, Sanders and McCormick, 1993). This was best demonstrated by a series of experiments conducted by Garathewol (1953; 1954; 1957) who studied the relative conspicuity and response time effects of flashing and steady lights. He found that flashing lights were more conspicuous than steady lights, at least when the contrast between signal and background was low. Nickerson et al. (1968) cite other lab experiments (Brown and Gibbs, 1958), which suggest that steady lights are superior to flashing turn signals in terms of conspicuity. The authors point out that discrepancies in findings could be attributed to the experimental parameters used in lab settings.

The conspicuity of flashing lights is also determined by the context in which they are viewed. A steady background is superior to a setting where other flashing lights are present (Crawford, 1963; Nickerson et al., 1968; Proctor and Zandt, 1994). Crawford (1963) investigated the effects of steady, flashing, relevant, and irrelevant (background) signals on the detection times of observers. He found that the benefits of implementing a flashing light (quicker response times) were lost if even one other flashing light was present in the background.

Urgency portrayed by flashing lights. There have been varied recommendations in the human factors literature concerning flash rate. In a series of lab experiments, Garathewol (1953; 1954; 1957) found that 3 Hz was particularly conspicuous. Others suggest a sense of urgency is portrayed if short duration rapid-frequency signals are presented, set at around 4-5 Hz, with equal on and off times (Van Cott and Kinkade 1972). Sanders and McCormick (1993), however, recommend one flashing light (between 3-10 Hz) for occasional emergencies or new conditions. It has also been known for some time that frequencies of 2-20 Hz appear brighter than the same lights shining steadily. This phenomenon is known as brightness enhancement and is often referred to as the Bartley effect (Bartley, 1961). In fact, the greatest degree of brightness enhancement occurs at around 10 Hz (although luminance and other variables need to be taken into account). Unfortunately, alpha rhythms in the brain have a frequency from 9-12 Hz and viewing this rate of intermittent light can trigger seizures in epilepsy sufferers (Howett, Kelly, and Pierce, 1978). The Epilepsy Foundation of America (EFA) suggests avoidance of a slightly different range of 10-20 flashes per second. Sleep deprivation and peripheral viewing of a flashing light can also result in more pronounced seizure attacks, according to the EFA. People who are susceptible to this "strobe effect" are not allowed to drive under current tight driver licensing laws which commonly require epilepsy sufferers to be seizure free for a specified period, together with a physician's evaluation of their ability to drive safely. However, they may still be exposed as passengers.

Lights viewed at above 15 Hz start to fuse and appear steady. As a result, most designers recommend rates between 1-3 Hz. This is mainly for psychological reasons. Speed and urgency are not associated with flash rates up to 1 Hz and so these are not effective as a warning signal. In aviation, popular frequencies are in the range of 1.2-1.5 Hz (72-90 fpm). These frequencies are not high enough to achieve the psychological impression of urgency, but are low enough to not induce seizures. Generally, 1-3 Hz rates are inferior in terms of visibility, but conservation of power has led to this design specification. Frequencies of 4-6 Hz would be just as effective at improving conspicuity (Howett, Kelly, and Pierce, 1978). It is also important to note that, according to Moore and Rumar (1999), a flash frequency of 3 Hz may trigger epileptic seizures in children. Although not relevant to all types of warnings, these factors concerning flash rate need to be considered in the driving environment due to the potential risk of seizure activation to children, pedestrians, and passengers.

Signal colors. Morgan et al. (1963) suggest the use of red for use in warning light design. However, in environmentally diverse situations, the authors recommend the use of pairs of colors (e.g., white on red) for effective detection of signals. In transportation, however, red is commonly recommended due to its associated meaning of danger, and its predominance in established vehicular warning signals, since white and red are used to indicate the front and rear respectively, of any vehicle. However, the literature on color presents conflicting results on the effectiveness of various colors, particularly red, in the conspicuity of rear signals.

There is typically seven times more luminous power in a red light than in a blue light. This is due to the use of a red filter, which passes 20% of the luminous energy of incandescent lamp light as opposed to 3% passed by a blue filter. This fraction is known as luminance transmittance

(Howett et al., 1978). If these colors are to be effectively tested for their conspicuity, the blue light needs to have seven times the luminous intensity as the light used for the red filters. If a strobe is used, the luminance transmittance for a red light is reduced from 20% to 13%. A clear filter allows 90% luminance transmittance for both incandescent and strobe lamps (Howett et al., 1978). When anti-collision strobe lights were first used to enhance the conspicuity of aircraft, the choice of color was extensively debated. Most of the discussion centered on whether red or white should be used. Red was thought to provide easier recognition against an urban background, and was also less distracting to the pilot in hazy and cloudy atmospheric conditions, with reduced effects on dark adaptation on pilots. Those who supported white argued that intensity was lost through the use of the red filter as later demonstrated by Howett et al. (1978), and that flash tubes without filters were much more conspicuous against an urban background. Furthermore, the eye has greater peripheral vision for white light (Douglas, 1971).

Overall, however, primary coding of lights using color alone has been rejected by transportation research for three reasons. One is observer color vision. Approximately 2% of the male population suffers brightness loss at the red end of the spectrum. This has led some researchers to suggest the use of orange-red brake lights to increase conspicuity (Allen, 1964). Second is the desaturation of colors in haze and fog. Third is the limitations of peripheral vision. Researchers suggest that peripheral discrimination of colors is irrelevant (due to the decline of color recognition in the periphery). As a result, color discrimination is not an effective "attention-getter," even for those people with normal color vision (Hunt, 1952; Sivak et al. 1999; Moreland and Cruz, 1959) These findings have led to a general consensus that color be used as a secondary coding parameter with the basic lighting system being color independent - critical signals in particular should not be coded in terms of color alone (Holmes, 1971; Nickerson et al. 1968; Morgan et al., 1963).

Crawford (1963) demonstrated the problems associated with conspicuity if flashing warning lights are used in a context surrounded by other flashing lights. The same is true for color (Howett et al. 1978). For example, if a red light is used in an environment where red lights dominate the scene, a blue light would be more conspicuous as long as their intensities were comparable.

Signal positioning. Research conducted on the effectiveness of CHMSLs suggests that positioning brake signals close to eye fixations during driving is partly responsible for its success in attracting attention (Theeuwes and Alferdinck, 1995; Sivak and Flannagan, 1993; Sivak, Conn, and Olson, 1986). The human factors literature supports this theory in that, to attract the observer attention, the signal should be positioned as close to the operator's line of sight as possible (Proctor and Zandt, 1994; Morgan et al, 1963). Urgent warnings should be placed within 30^{o} of the operator's normal line of sight. Ideally, if located among other warning lights, the signal should have a unique location and be easily distinguishable from the other lights (Morgan et al., 1963). If the light is to be placed among other similar lighting arrangements, as seen in rear signaling, the geometric shape of the signals can positively enhance conspicuity (Howett et al., 1978; Theeuwes and Alferdinck, 1995).

Light intensity. Often intensity is a key variable in ensuring that a vehicle is conspicuous at great distances from the observer. Current luminous intensity of brake lights is specified at between 80-300 candela. The minimum intensity of 80cd was found to be effective as 91% of observers, at a viewing distance of 50 feet, could identify the signal (Sivak et al., 1987). The authors also found that reaction times of drivers were positively related to the driver's degree of uncertainty. In the case of a flashing imminent warning signal, however, deciding which intensity to use becomes more complex. It is important that this type of warning light should be bright enough to stand out, but not so bright as to startle the observer (Morgan et al., 1963). Douglas (1971) recommends effective intensities of 40-400 cd on flashing lights used to raise the conspicuity of stationary vehicles in the aviation industry. The upper limit was chosen to avoid dazzling observers.

Warning activation criteria. For an intelligent rear vehicle warning signal, the dilemma lies in determining a warning distance, which would vary according to relative speed and braking behavior of the two vehicles, thus allowing sufficient time for a driver to respond to a collision. If the distance is too great, nuisance alarms would eventually prompt drivers to ignore them in favor of their own judgement. Further complicating the matter is the fact that situations in which a warning would be triggered require different calculations. A pure distance approach provides little benefit. An HD system activated by objects in a specific warning range, for example, 150, 200, or 250 feet would inundate the driver with alarms. The degree of potential danger caused by driving too close to a vehicle in front can only be evaluated accurately by taking into account the speed of both vehicles. This introduces the concept of dynamic warning distance algorithms, which would be capable of monitoring objects at distances between the criterion and maximum range. These algorithms are useful to this study because approximate times can be derived from such computations to determine a safe time to present the warning to the driver (Knipling et al., 1993).

Knipling et al. (1993) provide computations for use in determining timely warning distances to drivers in LVS and LVM conditions. These computations are based on modeling of driver reaction times based on previous studies (Sivak, Olson, and Farmer, 1982; Taoka, 1989) and assumptions of vehicle braking capabilities. Two versions of the algorithm are presented here:

- Lead Vehicle Stationary (LVS) situations. This refers to situations where the lead vehicle is stationary (i.e., $V_L = 0$). The warning distance derived from using the computation is simply the required separation distance that allows the following driver to react and decelerate uniformly just behind the stationary vehicle.

  The expression is stated simply as:

$$D_W = (V_f^2/2a) + T_D V_f \qquad (2)$$

Where:	D_W	=	HD system warning distance (in feet)
	V_f	=	Velocity of following vehicle
	a	=	Deceleration rate of following vehicle (0.6g or 19.3 ft/sec^2)
	T_D	=	Total time delay before driver of the following vehicle initiates a full response (2.05 seconds)

- Lead Vehicle Moving/Decelerating (LVM) situations. In this case the warning distance refers to the separation distance such that after both vehicles had decelerated to a stop, the following vehicle would stop immediately behind the lead vehicle. This equation considers the measured speeds of both vehicles to produce the following expression:

$$D_W = V_f^2/2a_f + T_D V_f - V_L^2/2a_L \quad (3)$$

Where:	D_W	=	HD system warning distance (in feet)
	V_f	=	Velocity of following vehicle
	a_f	=	Assumed deceleration rate of following vehicle (0.6g or 19.3ft/sec^2)
	T_D	=	Total time delay before driver of the following vehicle initiates a full response (2.05 seconds)
	V_L	=	Measured velocity of lead vehicle
	a_L	=	Assumed deceleration rate of lead vehicle (0.35g or 11.3ft/sec^2)

The computations developed by Knipling et al. (1993) used assumptions about the alertness of the driver, reaction times, and vehicle capabilities.

Due to the prevalence of lead vehicle stationary (LVS) accidents, other researchers have approached the question of when to warn drivers by looking at time to collision. However, there is little agreement about the optimal TTC criteria for presentation of warnings to drivers. A study performed by Horst (1984) analyzed videotape footage of naturally occurring vehicle conflict situations and presented evidence to suggest that a time-to-collision (TTC) criterion of 4 seconds be used to separate situations where drivers unintentionally find themselves in dangerous situations from those where they remain in control. However, Nilsson, Alm, and Janssen (1992) conducted an experiment to compare three collision avoidance systems based on TTC activation in a car following task. Subjective ratings indicated that four seconds is too short as an activation criterion. Maretzke and Jacob (1992) supported this finding that drivers tend to start braking at around four seconds, which does not provide enough time to react to a warning presented to them. The authors therefore recommended a criterion of five seconds.

However, Hirst and Graham (1996) question the use of a fixed time-to-collision criterion. They recognize that TTC is speed dependent in that greater stopping distances are allowed at higher relative speeds. They argue that it does not take into account that for similar brake force it takes longer to brake to a stop from a higher speed than from a slower speed. They cite the work of Horst (1991) who conducted a field study requiring that subjects brake at the latest possible point while approaching a stationary object in order to stop in front of the object. He found that TTC increased with speed.

Hirst and Graham (1996) then performed an experiment and found that braking behavior can be influenced by collision avoidance warning systems. Subjects were asked to brake at the last possible point to avoid collision with a video image of a lead vehicle. Subjects braked earlier when presented with an earlier warning. In general, more false alarms arose with a five second TTC criterion, and they theorized the same would be true for a four second TTC criterion. The authors suggested that a three second TTC criterion would not be long enough. They suggest that a TTC between three and four seconds would produce warnings before the mean subject braking response at the highest relative speed. They also suggest another option of modeling the reaction times they obtained, and activating the warning at a TTC of three seconds plus one foot for every mile per hour of following car speed. Looking at the literature on this subject, this trade-off between nuisance alarms and avoidance performance is still not well understood and warrants further research (Knipling et al.,1993).

<u>The impact of perception-reaction times of drivers.</u> To further complicate warning activation criteria in the design of collision warning systems, reaction times are extremely varied (Dingus et al.,1998). Driver reaction times vary from 0.9 seconds for unexpected events with athletes as subjects (Davis, Schweizer, Parosh, Lieberman and Apter, 1990) to 1.6 seconds for 95^{th} percentile drivers presented with unexpected events using a more representative population (Olsen and Sivak, 1986). This wide variation would complicate a collision warning system design as reaction time becomes one of the many variables that has to be considered when determining the optimal time to display a warning. Davis et al. (1990) found that determining perception-reaction time may be a more complex issue. Their study found that perception-reaction time increases with following distance. Short perception reaction time during short

headways was thought to be a result of drivers paying more attention to the vehicle in front. Carney (1996) also performed a study that supported the criticality of warning timing in that those subjects who drove in the longest sensor ranges received the most false alarms, leading to increased reliance on the subject's own abilities to detect collision situations rather than on the system. However, who drove with the shortest range of 200 feet, received no false alarms, but were involved in a collision as the timing of the warning was too late for them to react. Collisions would increase if the driver were distracted for all conditions.

<u>The Limited Channel Model</u>. Dingus et al. (1998) suggest that the psychological refractory period phenomenon be considered when investigating an emergency warning. The earliest study of this phenomenon (Telford, 1931, as cited by Dingus et al., 1998) found that reaction time to a second stimulus was delayed considerably when presented in close temporal succession to the first (less than 500msec apart). The phenomenon was called the psychological refractory period as it was analogous to the refractory period of a single neuron that will not respond to a second input if stimulated in close succession with other inputs. As this inter-stimulus time interval is decreased, human information processing shows signs of increasing levels of overload. This delay in reaction time can be explained by the "limited channel model" of attention (Broadbent, 1958). This model attributes this delay in reaction time to the second stimulus as being due to the processing of the first stimulus. Until the first stimulus clears the "channel," ability to process the second stimulus is not as efficient. Furthermore, when the inter-stimulus interval is sufficiently short (for example, less than 100 msecs), a qualitatively different processing sequence occurs: both responses are emitted together and both are delayed (Kantowitz, 1974). Dingus et al. (1998) describe the phenomena as if the two stimuli are occurring so close in time that the second stimulus gets in the channel during acceptance of the first.

Dingus et al. (1998) suggest that it may be appropriate to apply this psychological refractory period phenomenen to model the effect of an emergency warning. They theorize that the driver may not always react in time to an emerging dangerous situation due to divided attention between in-vehicle secondary tasks, such as talking to a passenger or checking a speedometer. Given the presence of a collision warning device, an emergency warning would be triggered.

This is the first stimulus. The driver's reaction is in the form of renewed awareness as a result of the warning signal. The second stimulus would be the visual stimulus of the approaching rear end of the vehicle. The time reaction (accelerator release followed by braking) to this visual stimulus, if the stimulus is presented in short succession to the warning signal, may be delayed in comparison to one stimulus or a longer interval between stimulus presentation.

If these theories are true, a trade-off needs to be made between an attention-getting signal that refocuses driver attention to the hazard and a signal that could overload the driver at a critical point, proving detrimental to his response. As Hankey (1996) found, there are many alternative responses to a rear end conflict such as braking, steering, and accelerating. The same would occur f the two stimuli were presented in a different order (e.g., if the driver is presented with the warning after he applies the brakes). The driver would have a shift in attention from action to a new stimulus, which would also lead to an increase in reaction time (Horowitz and Dingus, 1992). Careful thought needs to be put into ensuring a warning signal is not presented too early or too late, as either may increase reaction time thus inhibiting brake response.

The Strobe Light as an Effective Warning Signal

Strobe light signals are unique among flashing lights in that they use a small amount of gas (usually xenon) rather than a filament of any kind. This gas can be heated very rapidly resulting in full peak light output in a few microseconds with an equally rapid decay. In other words, the light has the ability to flash at full intensity at a rapid frequency unlike other types of flashing light. As a result of this capacity, strobes have two important features. The first is that the strobe can be used as a way of enhancing our ability to see fast motions (as in photography applications). Second, the strobe can be used as an "attention-getter" to see structures (for example, an airstrip in darkness). This second feature has resulted in a huge contribution to safety resulting from the presentation of a conspicuous warning to operators in various areas of transportation.

Recall that Summala et al. (1998) failed to attract the attention of distracted drivers using regular incandescent brake lamps, and researchers have suggested that flashing lights would yield a better result (Dingus et al., 1998; Holmes, 1971). There has been little research that compares the effectiveness of strobes with incandescent lights in this respect, but what research has been done suggests that strobes (white in particular) are more conspicuous than regular incandescent lights when viewed in the periphery (Howett, 1979). Howett (1979) reports on psychophysical tests that were conducted to test the conspicuity of various types of lights, including strobes, for eventual application to emergency vehicle warnings. The author used a novel technique of conspicuity matching in which observers fixated straight ahead and viewed two flashing lights located at 100m (330ft) peripherally (one 20 degrees to the left, the other 20 degrees to the right). One of the two lights was always a reference light whose intensity could be changed by the observer until both lights appeared equally conspicuous to the observer. The lights were ranked on a scale of conspicuity based on these adjustable light intensities. The authors found a good correlation of 0.90 between ranks and the measured effective intensities of the lights. Results showed that white filters regardless of light type were more conspicuous in the periphery. Furthermore, both in daylight and at night, xenon discharge strobes yielded highest conspicuity with white and blue domes, with the lowest conspicuity for red, and intermediate conspicuity for the yellow dome.

Applications in transportation. Strobes have been progressively used in transportation to attract the attention of observers. These lights have been used mainly as a method of collision avoidance or enhanced signaling by improving the conspicuity of objects or vehicles.

The use of strobe lights has resulted in improved conspicuity in road signaling products such as traffic lights, intelligent highway signaling, and construction signs. Noyce and Fambro (1998) examined the effectiveness of a vehicle-activated strobe light as a sign enhancement at passive railroad grade crossings. Driver surveys, observations, and before and after speed study results suggested that the addition of a strobe to the sign attracted the attention of drivers more effectively, thus raising awareness of the passive highway-railroad crossing. This enhancement resulted in more cautious driving and reduction of speed on approach. No adverse driver reactions were noted due to the implementation of the strobe device.

Strobes have also been used as a form of anti-collision warning device. These high intensity lights are used as a way of raising awareness of the presence of vehicles at safe distances away during poor visibility. Examples include snowplows, construction vehicles, and emergency vehicles. The most successful example of the use of a strobe as an anti-collision device is in the aviation industry. The strobe light is effective in allowing pilots more time to recognize and react to avoid collisions with other aircraft. The light does this by simply extending the range at which the conflicting target is visible to the human eye up to as much as 10 miles in daylight and approximately 75 miles at night. The white strobe light is also effective in the "Pilot Warning Indicator" system. This is an anti-collision warning device that senses the infra-red energy emitted from the flashing lamp source. Once detected, an auditory and visual display appears in the cockpit providing information about the approaching aircraft to assist the pilot in his reaction to the threat (Golden, 1971).

A final example is the use of the strobe light to raise the conspicuity of obstructions to advise or warn drivers of its presence. Examples include aviation landing aids, navigation aids, and TV towers. Farmer (1989) looked at the use of a strobe on the signal arms of school buses as a way of not only enhancing awareness that the bus was stationary, but also to discourage vehicles trying to pass while the bus was stationary. Farmer (1989) describes a study performed by the Tennessee Department of Education, in cooperation with Weldon Inc. and the Metro-Davidson County Board of Education. In this controlled experiment, stop arms with and without strobe lights were placed on buses for comparison. The numbers of passing cars while the stop arm was down was recorded over a three-week period. The results were convincing as 308 passes were made with traditional lighting as opposed to 12 with the installation of the strobe light. The results clearly established the superiority of the strobe in the stop signal arm (Farmer, 1989).

Research Approaches to Evaluation of Warning Systems

Studies that meaningfully investigate the effectiveness of countermeasures for rear end crashes are difficult to design. Many issues have to be addressed concerning how to conduct an experiment that produces valid data without compromising the safety of participants. Certain questions have to be asked in order to address these issues. How can system effectiveness be determined? How should these measurements be operationally defined (e.g., what constitutes reaction time and is reaction time the best measure of system effectiveness)? How can a safe and realistic scenario be presented (e.g., should a simulator or on-road test be used and if so, how is the element of surprise retained, if at all)? These issues have been addressed in many ways in the literature and what follows is a summary of these approaches. To ensure valid safe results, these approaches need to be considered when designing such an experiment.

Measuring effectiveness. Measures of stopping sight distance are used in highway design. At a minimum, this sight distance should be long enough to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. According to Fambro, Koppa, Picha, and Fitzpatrick (1998), stopping sight distance is derived from the sum of two components. The first is brake reaction distance/time (distance/time elapsed from instant of object detection to the instant the brakes are applied). Second is the braking distance (distance traveled from the instant the brakes are applied to when the vehicle has decelerated to a stop).

Brake response time (BRT) is the most commonly used measure in crash avoidance research to determine a system's effectiveness. It can indicate the accuracy and latency of driver response as a result of system implementation. Essentially, BRT represents the total time it takes a driver to detect an object, recognize it as a hazard, decide on a braking action, and initiate that braking action (Fambro et al., 1998). Brake response times are often used to measure the effectiveness of optimal rear lighting configurations such as CHMSLs (Theeuwes and Alferdinck, 1995), stopping sight distances used in highway design (Fambro, et al., 1998; Olson and Sivak, 1986; Taoka, 1989), and potential collision avoidance systems (Winters, 1998).

Perception Response Time (PRT) is also commonly used instead of or in addition to BRT. This is because a driver's initial response to a situation may not necessarily be a braking response. Participants may steer initially to avoid a collision and brake later. In operational terms, PRT means the time interval from the detection of a stimulus to the time the subject responds (Olson and Sivak, 1982; Hankey, 1996; Lerner, 1993).

Using BRT or PRT effectively removes vehicle-specific factors from evaluation of these systems. However, these measures do not take into account potential changes in driving habits that result from the use of the system. They may also be risky measures due to variations caused by differences in methods, subjects, and field settings (Tijerina, 1995). Winters (1998) points out that variations in equipment and experimental designs have lead to a variety of operational definitions for BRT measurement. Winters (1998) suggests that the definition of response time seems to be dependent on the type of testing environment. In field evaluations typical procedures used a controlled lead vehicle, which the participant followed. This type of procedure evoked operational definitions of reaction time as the interval between first detectable onset of the brake lights attached to the lead vehicle and first detectable onset of the brakes by the participant. However, simulator tests seem to break this BRT more effectively into smaller intervals which facilitate fuller understanding of braking behavior (Theeuwes and Alferdinck, 1995).

Deception. Deception is often necessary to avoid bias and anticipation effects. Lerner (1993) deceived participants by using the guise of judgement of road quality whereby periodically, at stop signs, participants were asked to judge the quality of the road sections they had just traveled. Winters (1998) also deceived participants by presenting them with a handling course. This meant that they could inform participants of risk, but did not have to specify the exact nature of this risk. Sivak et al. (1986) asked drivers to simply drive a test track to become accustomed to the test vehicle, and that the purpose of the study was to simply record driving performance.

Participants. With respect to studies of this nature a wide age range is always expected from the pool of participants recruited for these experiments. This is due to reports of statistically significant differences in mean response times for younger and older driving groups (Fambro et al., 1998). The criterion used to differentiate the younger and older drivers tends to be up to the discretion of the experimenter. Wide variations between studies have been found. For example, Olson and Sivak (1986) recruited two wide age ranges, 18-40 and 50-84 years of age, whereas Fambro et al. (1998) selected a narrower range of under 25 as the criterion for younger drivers and over 55 for older drivers. Lerner (1993) went further by recruiting three age groups of 20-40, 65-69, and over 70.

Testing environment. Whatever the purpose of a study that investigates driver response time to a particular stimulus, be it a signal or obstruction, reliability and validity of such measures are more accurate if measured in a real world environment. Indeed, responding to an emergency braking situation in any kind of simulator can be a very different experience. Realistic presentation of visual stimuli, such as a strobe, is also very difficult due to problems in resolution. Simulators do, however, provide many benefits. According to Winters (1998), more accurate measurements of quantities such as velocities and location of all traffic participants are possible, and there is generally greater control over the driving environment. Of course, the most important benefit associated with simulators or lab experiments is one of safety.

Winters (1998) argues that the gap between simulated and real world settings can be reduced through careful design and execution of a real-world scenario. Valid results are not always possible with the use of a simulated environment. When driving a simulator, participant expectancy of a collision tends to be higher, which can significantly affect response times as demonstrated by two Swedish researchers, Johannsen and Rumar (1971). The authors collected reaction times in both anticipated surprise (mean=0.54 secs) and unexpected surprise conditions (0.73 secs) for drivers on rural Swedish highways. These reaction times were measured in response to an auditory signal. Using this data, Jahanssen and Rumar (1971) developed a correction factor for the relationship between surprise and anticipated reaction time. They derived a multiplier of 1.35 which they recommended be applied to data collected under anticipated perception-response times to produce a database of surprise perception-response times. Winters (1998) points out that this correction factor is only valid for simple reactions and it is important to take measurements applicable to actual traffic situations.

Obstacle presentation. Presenting obstacles in real world environments as a way of evoking braking responses to a stimulus can be problematic due to issues of safety. Lightweight barrels have been used in past research as a way of eliciting unexpected emergency braking behavior (Lerner, 1993; Winters, 1998; Fambro et al., 1998). Moving targets were thought to be superior to stationary objects as a way of avoiding anticipatory responses (Winters, 1998). Lerner (1993) presented the barrels at approximately 200 feet in front of the vehicle, providing a time to collision criterion of 3.4 seconds at a speed of 40mph. Although the barrel in this case appeared to be rolling into the road it was tied by a set of chains to the shoulder area. Winters (1998) chose a slower speed of 15mph (22 feet per second) to prevent purely steering responses observed by others (such as Lerner, 1993), with an approximate TTC of 1.9 seconds. Both experiments took place in enclosed environments. Winters (1998) had truck drivers drive around a parking lot, whereas Lerner (1993) arguably had a more realistic environment in the form of a closed section of roadway.

Previous research concerning rear signaling has mainly been performed in laboratory settings (Meatyard, Fowkes, and Wall, 1988; Sivak et al., 1987; Theeuwes and Alferdinck, 1995). There have been increasingly more on-road trials regarding the perception of rear signaling where lead vehicle following scenarios are used and the lead vehicle unexpectedly brakes at some predetermined point in time (Summala et al., 1998; Sivak et al., 1982). Summala et al. (1998) conducted research, particularly relevant to this study, to determine whether distracted drivers would perceive a lead car's brake lights. They used a combination of headway distances which the participant had to maintain throughout the experiment. The first required that the participant maintain a headway of 15m with both vehicles traveling at approximately 18mph (1.8 seconds headway), the second at 30m headway, also traveling at approximately 18mph, and the third at 60m headway with both cars traveling at 37mph. The participants had to react to the lead car, which braked at an average deceleration rate of 2.1 ms^{-2} with the brake lights either working normally or switched off.

CHAPTER 2: RATIONALE AND RESEARCH OBJECTIVES

Rationale

The concept. Mortimer (1997) proposes two basic criteria for the design of vehicle rear lighting systems. First, lights should be coded to alert the following driver. Second, the nature of the information presented should be of the greatest value to them. Research has found that conventional systems fail to achieve these two criteria with any real effectiveness, which is arguably reflected in the rising rate of rear end collisions (NHTSA, 1998). This is due to perception difficulties associated with the design of conventional rear signals (Summala et al., 1998) as well as the failure of current systems to meet the limitations of humans in detecting closing rate information (Janssen et al., 1976; Lee, 1976). New rear signaling countermeasures such as CHMSL's and ABWS have been introduced as a way of providing perceptually easier to detect alert systems, essentially attempting to satisfy the first of Mortimer's criteria. Collision avoidance warning systems have tried to satisfy the second of these criteria by providing valuable information by issuing in-vehicle signals to alert the driver about closing rate. It is hoped that a strobe signal would provide improved conspicuity. Future benefits could be to provide information to a driver that their current closure rate and/or headway will result in an imminent collision if appropriate actions are not taken. From the literature reviewed there is no such imminent warning system currently undergoing investigation or in use.

Carney (1996) supports the use of a rear signal as an imminent rear-warning signal instead of an in-vehicle signal. Carney tested a collision avoidance device that used an in-vehicle gradual warning display through a series of nine multi-colored bars representing the relative proximity of the following vehicle to the vehicle in front. As the display showed red bars (an imminent warning) the system would respond with an auditory warning to brake. For all of the events tested, however, including imminent collisions, the participants would release the brake pedal before the system responded. This led Carney to conclude that participants were using information primarily from the visual array to determine their response and not an in-vehicle warning. Lee (1976) supported this interpretation in his analysis of perceptual features associated with rear end crashes. He determined that the visual array was the primary source of information that the driver reacts to automatically. Time to collision is one such important perceptual factor, derived from the optical array that leads to this reflex response, used heavily by drivers to assess the urgency of a situation in terms of when and how hard to brake. It is this kind of information that has led to this investigation, as theoretically the use of a warning in the optical array would increase the speed of response and decrease the severity of the collision.

An imminent warning has been chosen based on the work of Dingus et al. (1997) and Lee (1976) who suggest the potential usefulness of an imperative signal. Lee (1976) goes further to suggest that the rear of the car (including the lamps) needs to be redesigned to include an imperative signal, initiated when the following driver must brake. This is due to the problem with conventional lights in that they provide no information on when to brake, how hard to brake, or whether it is necessary to brake at all. Lee (1976) explains that drivers have to rely on direct (non-coded) visual information about how fast they are closing in on the vehicle in front. In some situations this coding is probably inadequate. An imperative signal informing the following driver to brake hard or stop would require additional coded information (Lee, 1976). Lee (1976) points out that the driver could be only a short time away from the vehicle in front before he/she is able to pick up closing information. As a result the driver might start braking too late.

Flashing lights have been recommended as attention attracting devices in many applications by researchers in this field (Dingus et al., 1998; Horowitz, 1994; Nickerson et al.,1968, Holmes, 1971; Sanders and McCormick, 1993; Morgan et al., 1963; Garathewol, 1953, 1954, 1957). The choice of a strobe device rather than a normal flashing light has been made due to its success over flashing incandescent lights in enhancing conspicuity in other surface transportation applications (Howett, 1979; Golden, 1971; Noyce, and Fambro, 1998; Farmer, 1989).

Finally, if found successful, there are many possibilities for future refinement and investigation into various configurations of such a signal. For example, integration of this type of signal into a collision avoidance system that could alert drivers of dangerous closure rates would provide drivers with essential information they cannot necessarily determine themselves. Mortimer (1990) found that at large distances, drivers make judgements of closure to the vehicle in front based on the visual angle. Drivers can detect differences as small as 0.12 (Weber ratio) meaning that if the headway is 100, a change of less than 12 meters cannot be detected. The driver can detect closure at large distances but does not get good information on the rate of closure until the vehicle ahead is too close to avoid an accident. It is envisioned that a device that initiates an alerting signal before the vehicle is too close would remove some of the guesswork and danger from car-following behavior.

Objective.

This is a "proof of concept" study. The strobe chosen for the purposes of this study was intentionally large, bright, and flashed at a rapid rate to maximize any potential positive effects of this type of light. The goal of this study was not to compare signals, nor was it to assess this particular strobe design, but to consider the potential of a strobe light to impact driver behavior in a way that may prevent rear end conflicts. The degree of success of the light at alerting subjects and eliciting faster response times will determine the seriousness with which strobe lights can be considered and refined in future research as a feasible alternative to conventional rear lighting systems.

In order to achieve these objectives it was essential that the experimental study was safe, reliable, and valid. As mentioned previously, an on-road study was the prefered setting to avoid anticipatory effects, and also provided a more accurate and realistic presentation of the strobe. Recall that Winters (1998) argues that the gap between simulated and real world settings can be reduced through careful design and execution of a real-world scenario. This study proposed presentation of this visual stimulus in a controlled on-road experiment through the unexpected presentation of a surrogate vehicle. This vehicle, like obstacles used in other studies of unexpected braking behavior, was collapsible and lightweight. In light of previous studies and recommendations concerning safe warning distances, the obstruction was presented to a driver at low enough speeds in a timely fashion so as to avoid the possibility of impact, yet evoke an emergency braking response.

Research Questions

As mentioned previously, the overall goal of this study is to determine whether a strobe signal can be successfully applied to a rear end conflict scenario to indicate imminent danger.

The experimental study was developed with several research questions in mind. These are as follows:

- To what extent does the strobe signal alert an inattentive/distracted driver to the presence of an obstruction? It is hypothesized that the strobe will improve conspicuity of the stationary surrogate vehicle. Consequently, it is anticipated that there will be a statistically significant decrease in the time to first glance at the surrogate vehicle, and the perception times of participants due to the presence of the strobe.

- To what extent does the use of the strobe affect response times? It is hypothesized that due to improved conspicuity and urgency conveyed by the signal, there will be a statistically significant decrease in response times.

- To what extent will drivers of all ages benefit from the strobe warning? It is hypothesized that participants of all age ranges will benefit (i.e., have quicker response times) because of exposure to the strobe warning.

- To what extent will older participants' response times change? It is hypothesized that older subjects will have poorer response times than younger participants. While it is anticipated that both age groups will benefit from the strobe, it is also hypothesized that this difference in response times between younger and older participants will remain the same between the strobe and no strobe conditions.

- What are the driver's opinions on this warning signal? Questionnaire data will provide the relevant information to answer this research question. It is hypothesized that opinions concerning the warning signal will be positive.