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Evaluation of Enhanced Brake Lights Using Surrogate Safety Metrics

Task 1 Report:
Further Characterization and Development of Rear Brake Light Signals

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16. Abstract

This report details a series of interrelated research studies and supporting activities (performed under Task 1) intended to further characterize and develop rear brake light signals likely to improve driver reaction to hard braking lead vehicle events, emphasizing unique and novel approaches not previously studied. The first study, LED optimization, characterized a sample of existing, commercially available automotive LED brake light arrays and documented the current state-of-the-art for LED technology. This work also developed optimized signal lighting configurations, including specifications for LED signal approaches (flash frequencies, brightness levels, patterns). The second empirical study (static testing) narrowed the pool of available signal approaches using static field evaluations intended to assess subjective impressions of signal attributes (attention-getting and glare) as well as eye-drawing capability of candidate signals for drivers who were looking away from the forward view. The third study (public roadway evaluation) captured driver responses to signal activations under naturalistic settings via observational methods using vehicles equipped with candidate signals and on-board instrumentation. This on-road study also addressed unintended consequences associated with the novel experimental signal approaches. Each step along this research path was intended to further refine signal attributes and narrow the set of candidate signals for downstream evaluation. Analytic activity was also undertaken in order to further the development of system specifications, including developing a scientific basis for activation criteria and thresholds and special cases for open loop enhanced rear lighting. Together, this work increased the state-of-knowledge and development of rear-brake signal approaches. Results indicate that newer rear signaling designs can be very effective at drawing drivers' eyes back to the forward roadway, and that flashing and brightness are two important signal properties moderating effectiveness (attention-getting). Significant performance gains can be achieved via use of LED signal approaches that both flash and increase signal intensity or lamp brightness.

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EXECUTIVE SUMMARY

This report outlines current efforts (third in the series) as part of the larger program of research intended to evaluate rear signaling applications designed to reduce the frequency and severity of rear-end crashes. The work discussed here builds on a series of findings from the preceding two Task Orders.

Previous Rear Signaling Studies Performed by VTTI

Task 1, published in February 2001 (Lee, Wierwille, & Klauer, 2002), was comprised of a literature review and focus groups used to help define the rear-end crash problem. Findings from this effort also assisted in narrowing the focus of subsequent research and frame the problem associated with rear-end crashes. Lead-vehicle-stopped crashes were found to be the most common, with the majority occurring in daylight under good environmental conditions. The most common causal factors were found to be inattention, distraction, and following too closely. It was also learned that capturing a driver's attention through use of a visual warning signal should include elements of flashing, apparent motion, size, color contrast, and luminance contrast. Candidate rear signaling applications were recommended for testing by a panel of experts in the subsequent Task 2 project. These efforts (Wierwille, Lee, & DeHart, 2005; Wierwille, Lee, & DeHart, 2003) focused on developing optimal candidate solutions both through static evaluations and on-road testing. Results from these studies indicated that a traffic clearing light (TCL) and an alternating pair were suitable for additional testing.

Later efforts involved examining the "100-Car" data to determine whether it provided any additional evidence in regard to rear-end crashes and countermeasures. Results suggested that the earlier approach was the correct one, particularly in regard to triggering and in regard to driver inattention (Lee, Llaneras, Klauer, & Sudweeks, 2007).

Work Performed Under Current Contract

Current efforts focused on the deployment of a real-world rear signaling application using LEDs not widely available during previous research. Several inter-related research activities were performed. The first characterized LED lighting from several automotive and heavy-truck applications. A round 4"-diameter heavy-truck stop lamp (red) was found to emit the highest on-axis illuminance output and was therefore selected for subsequent testing. A newer version of a TCL, pre-programmed with 12 available flash patterns (including steady state) and comprised entirely of LEDs was also tested. The experimenters subjectively rated each pattern for its attention-getting capability, and as a result four patterns were selected for inclusion in the static testing.

A second study (additional static testing) narrowed the pool of available signal approaches using static field evaluations intended to assess subjective impressions of signal attributes (attention-getting and discomfort glare) as well as eye-drawing capability of candidate signals for drivers who were looking away from the forward view. Testing included the use of increased intensity lamps that produced lighting levels above existing FMVSS levels. The best configurations based on the optimized frequency results and ensuing attention-getting and discomfort-glare ratings were as follows: (1) outboard lamps simultaneously flashing, CHMSL alternately flashing at 4.75Hz; and (2) all lights simultaneously flashing at 5.0Hz. Additionally, two other candidates were selected for additional testing based on demonstrated effectiveness: outboard lamps simultaneously flashing at 5.75Hz, CHMSL steady; and, outboard lamps alternately flashing at 4.25Hz, CHMSL steady.

Testing was then conducted comparing performance of the LED candidates to the previous overall top performer (incandescent TCL) using attention-getting and discomfort glare ratings as well as eye-drawing capability. Results showed that simultaneous flashing of all lamps at 5.0 Hz attracted fixations with greater frequency compared to the other conditions and was considered the optimal configuration for continued study. On the other hand, the steady-state baseline signal (ordinary brake lamps) failed to draw attention from a single participant. Coupled eye-drawing and interview data support the initial indication that simultaneous flashing of all lamps combined with increased brightness would be effective in capturing the attention of a driver engaged in a high workload task such as destination entry. These same data also show that the incandescent TCL is not as effective as the newer LED simultaneously-flashing rear lighting.

The final stage of testing was performed on public roadways, using a research vehicle, and represented the first controlled introduction of the candidate rear lighting signal to the naïve driving public. Three brake signal configurations were used:

1) Baseline (ordinary steady brake light level),
2) All lights simultaneously flashing at 5Hz with ordinary brake light levels, and
3) All lights simultaneously flashing at 5Hz with increased brightness.

The experimental vehicle appeared factory original, but was modified to accept the same type of LED lamps used in the aforementioned static testing. The study was designed to address several goals including benefits associated with the brake signals (i.e., understanding how drivers would respond to the candidate enhanced rear lighting conditions, and to determine the extent to which enhanced brake signals would capture and redirect driver’s eyes forward when they were looking away), as well as potential unintended consequences with their use. Results found that drivers exposed to the flashing with increased brightness were more likely to brake in response to the signal compared to conventional, steady brake level signals. This suggests that flashing with increased brightness represents a relatively strong cue. Very few events occurred in which eye-drawing capability could be measured; the sparse available data do suggest that flashing with increased brightness may be effective in reducing the incidence of long off-road glances. With respect to unintended consequences, vehicles in an adjacent lane were found to brake in response to both experimental signals more frequently than the baseline signal, but erratic behaviors of any kind were few.

The last section of this report addresses trigger criteria. These criteria include issues of triggering the signals going uphill or downhill, the decelerating/turning vehicle problem, the accelerometer noise problem, and triggering using ABS. Recommendations and justifications for how to deal with these issues are included.

In summary, this current effort proved effective in evaluating and selecting an optimum candidate signal application to address rear-end crashes. LED technology is sufficiently advanced and allows for optimized flash frequencies, which have been shown to improve attention-getting. Coupled with increased brightness, flashing all lamps simultaneously has the potential to command the attention of a following driver. This signal was also observed to induce following vehicle drivers to brake in response to its presentation.

Chapter 1. Introduction to the Current Rear Signaling Study

Background

In November 2007 Virginia Tech Transportation Institute (VTTI) was awarded contract DTNH22-05-D-01019, Task Order 14, by the National Highway Traffic Safety Administration to perform additional research in regard to rear lighting and signaling. This contract was the third that VTTI had received from NHTSA and was awarded because previous work had shown promise for reducing the number and severity of rear-end crashes.

Crash database studies had shown that more than 29 percent of all crashes were rear-end crashes, a figure that has remained steady during the past decade (National Transportation Safety Board, 2001; NHTSA, 2007). These crashes often result in serious injuries, loss of productive time, and high levels of property damage, particularly vehicle damage. Furthermore, these crashes often cause traffic congestion, resulting in reduced highway throughput. They occasionally result in occupant deaths, but the proportion is substantially less, contributing approximately 5.4 percent of traffic deaths in the United States (NHTSA, 2007). Secondary crashes are often a result of initial rear-end crashes, placing other drivers, emergency and law enforcement personnel, and anyone else near the original crash scene in jeopardy. Because of these figures, NHTSA determined that further research directed at reducing rear-end crashes should be undertaken. VTTI was tasked with examination of rear lighting and signaling aspects of the work. There has been ongoing work done elsewhere involving other approaches such as automatic crash avoidance and automatic braking (NHTSA, 2005). That ongoing work may also eventually contribute to lower rear-end crash rates.

Previous Program Efforts

The first study at VTTI was performed early in the millennium and showed that rear lighting and signaling had promise. Three major reports were produced, based on the results: Lee, Wierwille, and Klauer (2002), Wierwille, Lee, and DeHart (2005) and Wierwille, Lee, and DeHart (2003). These reports were eventually published by NHTSA to increase distribution. Each report is briefly described.

The Task 1 report was completed in February 2001 (Lee et al., 2002). It contained a comprehensive literature review, as well as focus group results involving law enforcement personnel and a trade study analysis. The conclusions of that report were as follows:

- Rear-end crashes are the most frequently occurring type of crash.
- Lead-vehicle-stopped crashes are the most common type of rear-end crash.
- The majority of rear-end crashes occurs in daylight under good weather conditions.

- Inattention, distraction, and following too closely are the most commonly cited causes of rear-end crashes.
- There are a multitude of ideas for enhanced rear lighting.
- Many of these ideas are repetitive, contain overlapping features, and do not address what is known about rear-end crashes.
- Human factors methods for capturing attention in a visual warning signal include use of flashing, apparent motion, size, color contrast, and luminance contrast.

The reader of the current report is encouraged to read this earlier document because it contains a review of rear lighting up to and including 2001.

An expert panel was assembled in later stages of the project and helped to examine candidate rear lighting ideas developed by the research team. The process resulted in the recommendation of three rear lighting configurations for optimization in Task 2 of the project. In making these recommendations, a distinction was made between two types of systems: open-loop systems in which parameters within (only) the lead vehicle are used to activate and de-activate the rear lighting, and closed-loop systems in which both lead vehicle and closing parameters associated with the following vehicle are used. In the latter case, some type of additional measurement system, such as radar, is necessary to obtain the additional parameters. For the three systems recommended, review by knowledgeable personnel suggested that the recommended systems should be made somewhat less complex so that they would be more practical. This guidance was considered as Task 2 was undertaken. It should be mentioned that both open-loop and closed-loop algorithms for activation and deactivation were developed during Task 1. These algorithms are contained in the Task 1 report.

The Task 2 report (Wierwille et al., 2003) describes two static experiments that were conducted with the idea of optimizing the attention-getting capability of proposed modified rear lighting. In the first experiment, 12 subjects evaluated 17 configurations. These configurations included variants of the Task 1 recommendations as well as baseline systems, including several highly attention-getting devices. The experiment was conducted using white lights and clear lenses to provide a consistent comparison across all configurations tested. The results showed that the traffic clearing light (TCL), a lamp with a motorized reflector moving in an "M-sweep" pattern was the top candidate for a high-level, enhanced brake light warning signal. An alternating pair was selected as an appropriate stopped/slowly moving signal. It should be noted that the first experiment covered the gamut in terms of numbers and types of lighting. Both strobes and high-output incandescent lamps were included. However, LED (light-emitting diode) lamps were not included because they had not been sufficiently developed at the time that the experiment was undertaken.

The second study performed under Task 2 used another (different) group of twelve subjects with clear, amber (yellow), and red lenses. Again, the TCL with a non-dispersive lens showed the greatest attention-getting capability. An alternating pair with high output halogen lamps and dispersive lenses showed good results for the stopped/slowly moving vehicle signal. The Task 2 report concluded that the TCL lens should be red, the alternating pair lenses should be amber, and that a three lamp bar with the TCL surrounded by the alternating pair should be the recommended configuration for road tests.

The final task for the project, Task 3, involved roadway evaluation of the final configurations (Wierwille et al., 2005). However, the alternating pair when used in Task 3 was re-considered after review to be an enhanced rear lighting system, like the TCL, and not a stopped/slowly moving vehicle system as had been originally planned. Consequently, a small additional static test preceded the road test, directed at optimizing the alternating pair as an alternative to the TCL. In other words, the road test was to be a test of two enhanced rear lighting candidates so that "all eggs would not be put in one basket."

In the preliminary experiment, modifications to the alternating pair were tested in a static situation using human factors experts. Results indicated that use of greater drive voltage and kick voltage improved the attention-getting capability of the alternating pair. Results also showed that that an alternating frequency of 4.0 Hz was optimal for the incandescent pair of lamps.

The main experiment was conducted on the Virginia Smart Road in Blacksburg, Virginia, using a surrogate vehicle containing conventional lighting and the two new enhanced rear lighting signal configurations. The surrogate vehicle was actually a shell built on a lightweight trailer. It was drawn by means of a 40-ft (12.2 m) boom by another vehicle in which the taillights had been disconnected. Seventy-two ordinary drivers, split into three groups, participated. Driver subjects were purposely distracted by in-vehicle tasks as the lead (surrogate) vehicle underwent hard braking. Responses were compared for the conventional and two enhanced lighting groups. Results showed improvements in brake activation times of 0.25 to 0.35 s, corresponding to 15 to 30 ft (4.6 to 9.1 m) of additional stopping distance for the enhanced lighting. The TCL was just slightly better than the improved alternating pair. Other measures suggested an eye-drawing effect created by the enhanced rear lighting signals, which explains how the faster response times were achieved. It should be mentioned that the on-road experiment was quite complex to set up and run, but the results do indeed show the promise of reducing the number and severity of rear-end crashes.

Work continued at VTTI under a new contract, awarded in 2003. The first task involved analysis of rear-end crashes and incidents using the so-called "100-Car" database (Lee, Llaneras, Klauer, & Sudweeks, 2007). The 100-Car database involved the use of 100 instrumented vehicles that were loaned to individual drivers (Dingus et al., 2006). There were numerous collisions and even more numerous near-crashes and incidents. The database was "general purpose" but was set up in such a way that rear-end crashes, near-crashes, and incidents were encompassed. Consequently, it was a matter of properly extracting and analyzing the information that had already been recorded. Specific research questions were posted and answered using database queries.

Among the many conclusions of this study are the following statements, which are surprisingly similar to statements made in the results of the earlier project.

- Data suggests that rear signaling that draws the driver's eyes forward is likely to be successful. The reason is that drivers with longer eyes-off-road times were the ones most likely to become involved in rear-end crashes.
- Data suggests that lead vehicle enhanced rear lighting triggering for decelerations of 0.4 g or higher should capture a large proportion of the crash scenarios. The 0.35 g criterion suggested in the earlier contract would "capture" approximately 90 percent of all following-vehicle deceleration rear-end events (crashes, near-crashes, and incidents), and 60 percent of all lead-vehicle deceleration rear-end events.
- Data suggests that 81 percent of rear-end crashes were with lead vehicles that had stopped on the pavement. This indicates that a timeout signal should be used that continues the enhanced rear lighting for at least several seconds after the lead vehicle has stopped.

Task 2 of the second contract dealt with initial on-road tests and how to implement them. In particular the objective was to gain experience with an equipped vehicle used on public roads. A Ford Taurus was prepared for these tests. The top two rear lighting systems (a TCL and an Improved Alternating Pair or IAP) plus two baseline lighting systems were implemented in the vehicle. The lighting was activated whenever deceleration (on level ground) exceeded 0.35 g. It also remained activated for 5 s after deceleration dropped to 0.15 g or less. It therefore remained activated for an interval if the car came to a complete stop after substantial deceleration. This car was also equipped with data-gathering equipment that included two rear facing radar systems (Eaton Vorad) and three rear- facing video cameras with different fields-of-view capability. The fundamental concept was to drive in traffic and determine drivers' reactions to the equipped vehicle. Approximately 63 hours of on-road data were gathered using this pilot vehicle. Some of the conclusions drawn from the study were as follows:

- Video technology is currently sufficient to allow surprisingly good video data gathering of the following driver's face. This statement assumes daytime use, which is when most rear-end crashes occur.
- It is important to obtain, through data reduction, the number of incidents and near-crashes (defined similar to definitions provided in the 100-Car study) because it is unlikely that there would be any crashes with a single, equipped vehicle.
- Measures of eye-drawing capability of new lighting arrangements should be obtained. However, other measures such as deceleration of a following vehicle are also important.

Additional findings were also obtained:

- Road grade (that is, going uphill or downhill) should be taken into account in triggering criteria. Although not stated in the report, this problem is more complicated than it first appears because stopping distances are decreased going uphill and are increased going downhill. Of course there is also the problem that the deceleration sensor will pick up a gravity component unless it is gyro-stabilized or otherwise appropriately compensated.

- The timeout feature should be improved, with particular emphasis on decelerating and then turning. The problem is that, on a turn, another following vehicle may be directly behind the equipped vehicle, and the driver of this following vehicle may have no idea as to why the emergency lighting was activated. In such cases, the timeout should be terminated earlier than usual.

- The equipped vehicle should look as "normal" as possible, so that it does not draw attention due to curiosity prior to lighting activation. Lighting should be integrated and should appear to be production lighting (prior to activation) if at all possible.

- It is important to implement any enhanced lighting as it was intended or designed in static tests. If parameters are allowed to vary, such as applied voltage or frequency, there is then no history of effectiveness. In other words, the transfer of an optimized design to a vehicle must preserve the essential elements. Otherwise there is no step-by-step logical progression of events.

The Task 2 results provide a good deal of information in regard to how to transfer results from static tests to initial on-road tests

Task 3 of the second contract went further into detail regarding how on-road tests should be carried out. It described the steps necessary to obtain analyzable data that would indicate whether or not the enhanced rear lighting was likely to be effective. Steps in the process would include development of prototype vehicles, refinement of data analysis tools and radar units, and performance of Smart Road initial testing. The layout of these tasks is quite complex and suggests that a good deal of planning and engineering will be necessary. For example, the problem of data downloading has not been previously studied for enhanced rear lighting and would need to be examined in detail.

The Task 3 report also suggests that limited pilot testing should be undertaken to support development and implementation procedures needed for a large scale effort. It also provides the steps needed to deploy vehicles in a large-scale effort, that is, a field operational test. The reading of these reports associated with the second contract makes clear that there is much to be done before a multivehicle field operational test can be undertaken.

Current Program Work

The current, ongoing research embodies an attempt to begin the process of deployment. Work began with a series of stakeholder and industry workshops (e.g., automotive manufacturers, suppliers, safety experts, and government regulators) intended to provide the opportunity for individuals to share their experience regarding rear signaling system concepts and designs, as well as provide valuable insights on previous project work and future directions (Appendix A). The virtual workshop was designed to foster discussion and gather information on key issues, including: candidate system functions and operational concepts for enhanced braking lighting, feasibility of rear brake light concepts, need for standardization of signals, and metrics and methods for evaluating enhanced rear brake light systems. Participants expressed the desire for the program to explore both incandescent and LED configurations, and attempt, to the extent possible, to take advantage of existing brake lamp frameworks/housings. Attendees also recommended that evaluations measure unintended consequences associated with the introduction of any new signals in addition to performance benefits, and to standardize relevant, performance-related functional system characteristics such as triggering criteria (refer to Appendix A for a detailed summary of the stakeholder workshops).

Insights into candidate concepts, system designs, and recommended research were also provided, including new developments that need to be considered. In particular, LED (light emitting diode) technology has come a long way in recent years. This technology is in use on rear lighting assemblies of current automobiles. The question to be answered is whether LEDs would have sufficient output to be used in enhanced rear lighting systems. Such systems require a higher on-axis output. If LEDs can be used for enhanced rear lighting, then methods should be developed to optimize their use and to consider how they should be integrated into the vehicle rear-end structure.

This report describes studies undertaken to assess LEDs and to determine which type and configuration provides the greatest advantages for rear-end enhanced rear lighting systems. Also, in the time interval since the initial contract was completed, an LED TCL (traffic clearing light) has been developed. It was decided to evaluate this new type of TCL as well. The first study deals with brightness evaluation of various LED candidates and second deals with frequency optimization and pattern selection (Figure 1). The second study uses some of the brighter LED arrays in static human factors evaluations intended to determine optimized frequencies and patterns.

Thereafter, optimized patterns are re-selected so that they allow comparison with previously proposed configurations, including the *incandescent* TCL and a promising pattern proposed by an automobile manufacturer. In addition, a baseline lighting configuration is included in the comparison. The patterns are tested in a static human factors experiment intended to determine the eye drawing capability of the various configurations. Eye-drawing capability is believed to represent the most effective means of redirecting a distracted driver's attention to the forward view when a rear-end crash is imminent.

Thereafter, this report shows how a vehicle was implemented using LED technology in such a way that viable candidates could be tested in normal traffic. This process involved implementing the vehicle with both the LED technology for rear lighting and data-gathering equipment, and then having researchers drive the vehicle. There were two important objectives in this experiment: determining eye-drawing (to the extent possible), and evaluating following driver behavior.

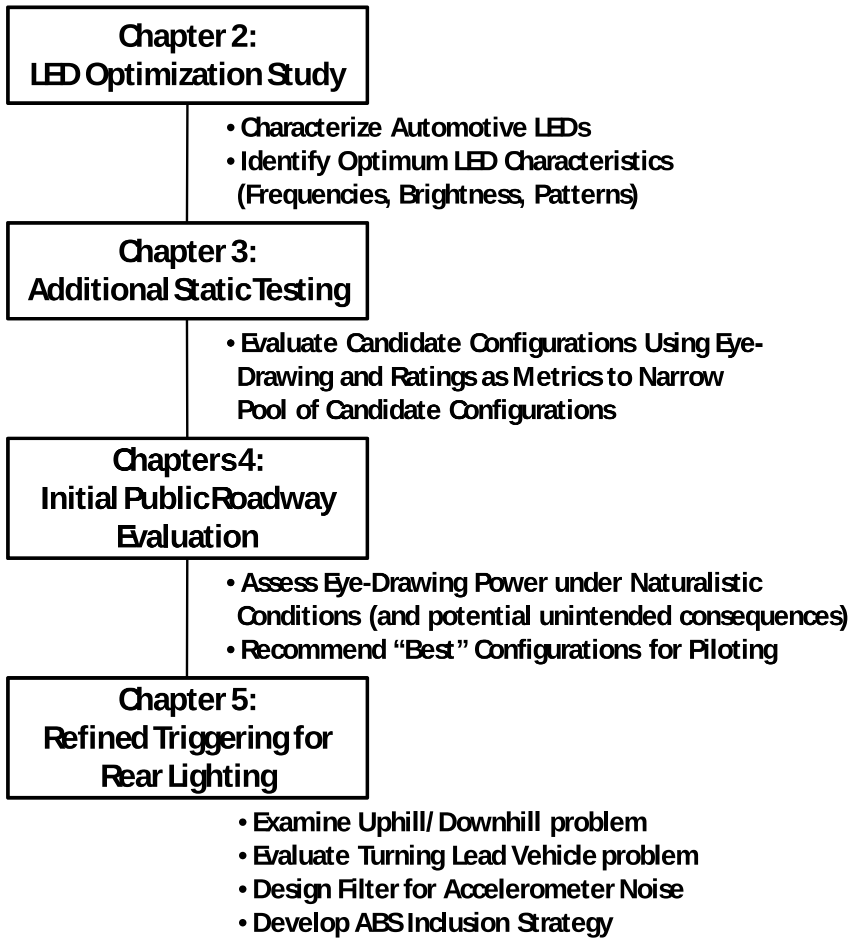

Figure 1. Studies Undertaken in Phase 1 of the Current Contract

Test conditions included the "best" configuration as determined from static tests, as well as a baseline configuration and one that was a candidate proposed by a manufacturer. The results are presented and show that eye-drawing capability is difficult to measure in traffic; nevertheless what results were obtained were positive for the "best configuration." In addition, following driver behavior was generally favorable.

An additional chapter of this report follows the experimental work and proposes solutions to other problems that are known to occur with open-loop rear lighting systems (those that take parameters from the equipped (lead) vehicle only. This chapter shows how to handle some of the difficult problems associated with rear lighting triggering.

Review of the Rear-End Crash Problem: Roadway and Traffic Factors

Analysis of 100-Car data (Lee, Llaneras, Klauer, & Sudweeks, 2007) found that most drivers are attentive and able to detect and respond to a stopped or decelerating lead vehicle. Data suggests that failure to respond (or delay in responding) to a stopped or decelerating lead vehicle is generally a result of distraction, and in particular, improper allocation of visual attention. Thus, VTTI's approach to the rear-end crash problem has argued that a successful rear signaling system would work to redirect driver visual attention to the forward roadway (for cases involving distracted drivers), as well as improve the driver's ability to discern hard braking events by increasing the saliency or meaningfulness of the brake signal (for attentive drivers).

In regard to roadway and traffic factors, the literature suggests that most rear-end crashes occur during daylight hours on dry roads (e.g., Misener, Tsao, Song, & Steinfeld, 2000), at or near junctions or intersections, and on straight roadways as opposed to curves (Knipling, Wang, & Yin, 1993). Analyses of the 100-Car data also tend to support these general findings showing that (Lee et al., 2007):

- 67 percent of crashes occurred when the roadway surface condition was dry;
- The overwhelming percentage of rear-end crashes (74%) occurred in daylight;
- Over 76 percent of rear-end crashes occurred on roads marked as level;
- Over 60 percent of crashes occurred in intersection and intersection-related locations; and
- Over 60 percent of the rear-end crashes occurred in uncongested or low-density traffic conditions (free flow and flow with some restrictions).

In consideration of the above, it appears that eye-glance patterns (moderated by distraction), not roadway or traffic factors, are the most significant predictor of whether a near-crash situation evolves into a crash for conflicts with lead and following vehicles (rear-end crashes).

Chapter 2. Study of Present-Day LED Brightness and Corresponding Rear Signaling Concepts

Study Purpose & Objective

This study is part of a larger research effort intended to contribute to the development of enhanced rear lighting signals to reduce the incidence of rear-end crashes. The purpose of this study was to develop optimized signal lighting configurations using present-day lighting assemblies, but with LED technology. This involved determining optimum flash frequencies, brightness levels, and patterns (e.g., simultaneous versus alternating flashing). Because LEDs have much faster illumination and extinguishing characteristics, optimum frequencies may be different from those for incandescent lamps that were previously examined and characterized.

Study Design

Work under this study included a laboratory component to quantify the brightness of various LED lamps, and a data collection component using human participants (Figure 2). Each component is detailed below.

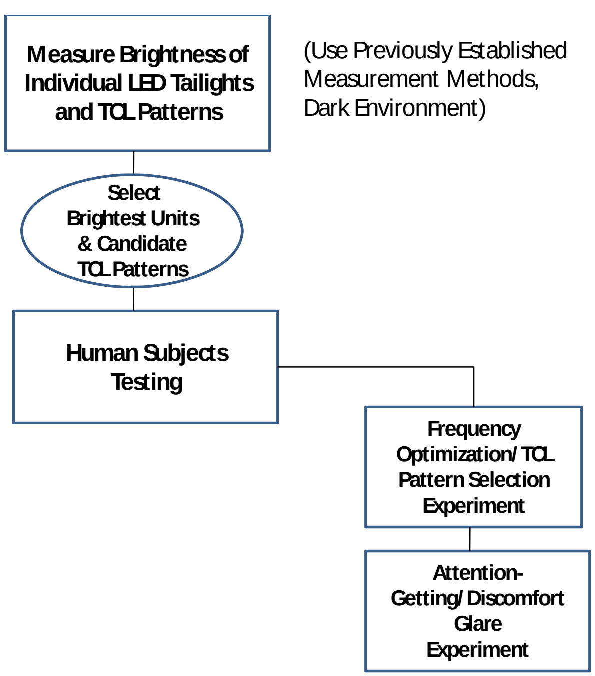

Figure 2. Framework of Research Activities

Laboratory Evaluation of LED Brightness

The first step was to characterize a sample of existing, commercially available automotive LED light arrays and to evaluate the current state-of-the-art of LED technology. VTTI acquired several large array rear lighting LED taillights from production vehicles and marker light assemblies ordinarily used on heavy vehicles. In addition, a Delta Ray traffic clearing lamp used on law enforcement vehicles was evaluated. This lamp is herein referred to as the LED TCL. Evaluations took place in a controlled, darkened environment using the same measurement methods that were used in earlier efforts to document the brightness levels of incandescent lamp arrays.

LED Brightness Study

In this study a wide variety of LED taillights and other marker and directional signal assemblies were evaluated using an illuminance meter. This meter was placed on a tripod, exactly 8 m (26 ft, 3 in) away from the taillight or marker assembly (hereafter called the source). The source was powered at 13.5 volts, and the steady state current draw was measured. The 13.5 volt value was selected as being representative of most automotive electrical systems (while running). A few vehicles use slightly higher voltages, while others use slightly lower voltages. However, 13.5 volts is probably the most representative.

The source was aimed directly at the meter. This measurement was referred to as the on-axis reading. It was determined experimentally by adjusting the angle of the source in both the horizontal and vertical planes until the maximum reading was obtained. This reading was then recorded. Thereafter, the source was rotated in a horizontal plane (only) in both rotational directions until the readings on the meter were half that obtained for the on-axis reading. The two half-output reading points were defined as representing the horizontal beamwidth.

Luminous output was measured in lux. After data was gathered, these values were converted using the standard equation:

$$\text{Equivalent source output (cd)} = \text{reading (lux)} \times \text{distance squared } (m^2)$$

This equation provides the equivalent output in the direction measured in candelas (cd).

It is important to mention why the readings were taken at 8 m. At this distance, the "far field" pattern of the source output is established. In other words, the pattern does not change as a function of angle beyond 8 m. However, it is still possible to obtain substantial readings and to be able to find a closed environment that could be darkened, so that stray light does not affect the meter readings. Another element of importance was the tint of the sources. In all cases, red-tinted sources were used. In some cases the LEDs themselves gave off red tinted illumination viewed through a more-or-less clear plastic lens. In other cases, the lens was also tinted. It is believed that all of the sources used LEDs producing red light.

The meter used to measure the output of each source included a photopic characteristic curve. The photopic characteristic was integral to the meter. It therefore had the effect of mimicking the human eye in terms of sensitivity to red light. As is well known, individuals have a "scotopic" response characteristic when they are well dark-adapted. However, drivers at night experience several sources of light including their own vehicle headlamp reflected illumination, headlamp glare from oncoming vehicles, tail lamp lighting from vehicles ahead, and overhead lighting. Therefore, the photopic characteristic may actually be more representative of night driving, and this characteristic was used for the measurements.

The results of the measurements are summarized in Table 1 for the various vehicle taillights and for special lights ordinarily used on cargo trailers. Note that the results in Table 1 are presented in descending order of on-axis light output, and that these measurements reflect the on-axis brightness levels of the lamps. The latter were evaluated primarily for use as CHMSLs (center high-mounted stop lamps). However, assuming their brightness was sufficient, they were also considered as candidates for use in the outside stop lamp units. As indicated in the introduction, a traffic clearing lamp was also evaluated. However, the results are presented later because of the need for additional explanation.

Table 1. Summary of Findings for the Laboratory Tests for Rear Lamp Assemblies and Heavy-Vehicle Marker Lamps

Lamp Description		On-Axis Output Measurement at 8m (lux)	On-Axis Equivalent Source Output (cd)	Half Output Total Horizontal Beamwidth (degrees)	Number of Active LEDs	Approximate On-Axis Output per LED (cd/LED)	Current Draw at 13.5V (milliamps)	Power Consumed at 13.5V (watts)
Round 4" Diameter Stoplamp *Type: anythingtruck.com 440RHW*		4.11	263	7	40	6.58	271	3.66
Oval 2"x6" markerlamp *Type: Maxxima M63100R/Y (www.delcity.net)*		2.55	163.2	24	60	2.72	436	5.89
Oval 2"x6" markerlamp *Type: anythingtruck.com 602R*		2.16	138.2	20.5	13	10.63	269	3.63
Vehicle A *Type: 2007 Mercedes CL600*		2.04	130.6	40	16*	8.16	347	4.68
Vehicle B *Type: 2006 Infiniti M35*		1.60	102.4	45	23	4.45	721	9.73
Round 4" Diameter Stoplamp *Type: Maxxima M42100R/Y (www.delcity.net)*		1.59	101.8	28	44	2.31	336	4.54
Vehicle C *Type: 2007 Acura RL*		1.38	88.3	27	28	3.82	489	6.60
Vehicle D *Type: 2007 Honda Accord*		1.31	83.8	49.5	15	5.58	242	3.27
Vehicle E *Type: 2007 Cadillac DTS*		0.50	32.0	71	31	0.97	376	5.08

*Compound LED subassembly

The two units with the highest output are lamps ordinarily used on heavy vehicles, one being round and the other being oval in shape. The units use large numbers of LEDs to achieve high brightness. Figure 3 shows the sources that were used for the measurements. Note that the relatively low on-axis reading for Vehicle E (2007 Cadillac DTS) may reflect the fact that the lamp design on this vehicle distributes the light over a very wide angle (71 degrees as shown in Table 1).

(a)

(b)

Figure 3. Rear Lamp Assemblies (a) and Heavy-Vehicle Marker Lamps (b) Tested for Brightness, Beam Width, and Power Consumption

In regard to the LED TCL, the output was again carefully measured. However, this unit comes standard with a dispersive lens used to spread the output of the LED TCL horizontally. Removal of this lens was straightforward, so it was tested both ways. Figure 4 shows the LED TCL with the front bezel and lens removed.

Figure 4. LED TCL With the Front Bezel and Dispersive Lens Removed, Mounted in Attachment Fixture With Clear Plastic Window

The LED TCL is a complex assembly with 12 possible patterns. These patterns are pin-programmable, sequentially. The user may select a desired pattern and store it in memory for recall anytime the unit is energized. Essentially, this LED TCL is a bilaterally symmetrical array of 84 LEDs in which subgroups can be energized and de-energized simultaneously, thus creating the various patterns. Most of the patterns appear as triangles. The unit is self contained and has its own electronics for creating the various patterns. It is only necessary to apply power to have the unit start up in the desired pattern, once the pattern is programmed. All LEDs in the unit tested produced red light. Other color combinations (red/green and red/blue) are available from the manufacturer, but all-red was selected as being most appropriate for a rear-facing system.

Initially, the unit was evaluated to pre-select the most attention-getting patterns, as judged by three researchers working on the project. To judge attention-getting, the researchers stood 100 ft (30.5 m) away and rated each pattern on a scale of 1 to 10, with 10 being the highest possible rating. Tests were run outdoors in the afternoon on a sunny day, but on the shady side of a large storage building. The sky illuminance was measured with the meter pointed up from the shade and found to be approximately 12,000 lux. Both the lens and bezel were in place for the tests, and the applied voltage was again 13.5 volts. One of the test configurations was a "steady" condition, which was not rated. In the steady condition all LEDs were illuminated. Another condition was an "alternating pair" in which all LEDs to the left of center were illuminated and then all LEDs to the right of center were illuminated, alternately. The steady pattern drew 1.5 amps, whereas all of the other patterns drew less than 1.0 amp. The patterns were cycled three times, once for observation by the researchers, and twice while each researcher rated. Each pattern was ranked on the basis of total rating points for the two ratings of each pattern. Thus, the highest possible summed rating was 60 and the lowest possible was 6. Table 2 shows the results of the rating process.

Table 2. Results of the Rating Process for Pre-Selection of LED TCL Patterns

TCL Pattern Number	Total Ratings Points	Rank
Steady; 0	(Not rated)	(Not rated)
5	46	1
10	45	2
4	40	3
1	34	4.5
3	34	4.5
Alt. Pair; 11	32	6
2	31	7
9	25	8
7	23	9
8	22	10
6	19	11

The concept behind the pre-selection task was to select the patterns most likely to receive the highest ratings in the later naive subject attention-getting tests. This pre-selection was intended to provide an indication of the most viable candidates. The table shows a relatively clear demarcation between the third- and fourth-ranked candidates, with a 6-rating-point drop in between. Thus, patterns 5, 10, and 4 were selected for use with naïve subjects. These three patterns were carried forward in the experimental design.

The alternating pair (pattern 11) was similar to patterns tested previously using incandescent lamps. For purposes of comparison, this pattern was also carried forward in the experimental design, even though it was ranked only 6th among the 11 patterns evaluated.

Once the patterns had been evaluated, the LED TCL was taken to a darkened laboratory for illuminance measurements. The LED TCL was first tested with the lens and bezel in place in the steady condition. Thereafter, the lens and bezel were removed and tested for both the steady condition and the patterns pre-selected in the outdoor evaluation. It should be noted that the outdoor tests were run with the lens in place. However, it seems unlikely that the pattern selection process would change with removal of the lens, because all patterns would be affected similarly; that is, all would have proportionally greater illuminance output on-axis or near on-axis.

The results of the darkened indoor laboratory tests for the LED TCL are presented in Table 3. The table shows that the lens had major effects on both the on-axis illuminance and on the beamwidth. When the lens was removed, the on-axis output increased markedly and the beamwidth became quite narrow.

Table 3. Summary of Findings for the Laboratory Tests for the LED TCL With and Without the Dispersive Lens and for Various Patterns (Average Values Are Shown for the Various Patterns)

Lens Use		Pattern	On-Axis Output Measurement at 8m (lux)	On-Axis Equivalent Source Output (cd)	Half-Output Total Horizontal Beamwidth (degrees)
Dispersive Lens in Place		Steady; 0	2.6	166.4	33
Dispersive Lens Removed		Steady; 0	7.2	460.8	8
		4	2.0	128.0	
		5	2.0	128.0	
		10	2.1	134.4	
		Alt. Pair; 11	3.9	249.6	

Analysis of the Laboratory Brightness Studies

Tables 1 and 3 show the on-axis illuminance outputs of the various sources that were tested. In general, those units with the highest number of LEDs have the greatest outputs. This suggests that to achieve even greater output, the number of LEDs should be increased or the lamp units should be "ganged." The tables also show that there is a tradeoff between on-axis equivalent output and beamwidth. Generally, concentrating the light output in a narrow beam causes the on-axis output to be higher, as expected. This result is best observed by comparing the entry in the top row of Table 1 with the entry in the bottom row. The top entry has the highest on-axis output and the narrowest beam, while the bottom entry has the lowest on-axis output and the widest beam. A similar finding can be seen in the first two rows of Table 3.

In regard to power consumed, the units are quite efficient, relatively speaking. Incandescent lamps having the same output would consume much greater amounts of power.

The outputs of the LED sources can be compared with the results of earlier tests using incandescent lamp assemblies (Wierwille et al., 2005). Results for the Improved Alternating Pair (of incandescent lamps) demonstrated an average output on-axis of 1,376 cd; this reflects a greater intensity than allowed by the FMVSS standard. It is clear from Tables 1and 3 that the LED assemblies are much below this. However, if the round unit that is the top entry in Table 1 is used in multiples, it should be able to compete favorably with the incandescent units, at least on-axis. Note that six units would be capable of providing equivalent outputs, even allowing for small mis-aiming and additional clear plastic cover attenuation in transmissivity. This comparison provides an indication of the direction in which to proceed. Table 3 shows that the LED TCL as a unit is somewhat less bright than the alternating pair, regardless of the pattern used.

Whether using the round stop lamp (top line in Table 1) or the LED TCL (Table 3) without the dispersive lens, it is clear that the horizontal beamwidth is quite narrow, that is, 7 to 8 degrees. It is reasonable to ask if such a beamwidth would have shortcomings in regard to effectiveness for attracting the attention of the following driver. Table 4 has been prepared using a 7-degree beamwidth. It shows that the beamwidth is adequate, and at near distances where the perceived intensity would be highest, drivers in adjacent lanes would observe a greatly attenuated output. Since drivers in adjacent lanes are not the ones who would collide with the lead vehicle, it is desirable that they do not receive the high intensity signal. Consequently, narrow beam output has advantages in that the beam does not in general greatly affect drivers in adjacent lanes at close range.

Table 4. Coverage as a Function of Distance for a 7-Degree Horizontal Beam Width

Distance from Source to Following Driver (ft)	50	100	150	200
Width of Beam (ft)	6.1	12.2	18.3	24.4

In regard to Table 4, if the following driver's vehicle is centered in the lane, his or her eyes would be approximately 2 ft (0.61 m) left of the center of the lane. The right rear outboard light assembly of the lead vehicle (also centered in the lane) would be approximately 2.75 ft (0.84 m) right of the center of the lane. Consequently, this assembly would be just outside the beam width at the 50 ft (15.24 m) distance. However, small aiming inaccuracies are to be expected for the individual units. Therefore, it is quite likely that even at 50 ft (14.24 m) there would be sufficient output to warn the following driver. In addition, the opposite outboard lamp and the CHMSL would be well inside the beam width.

Development of the Outdoor Test Apparatus

Table 1 shows that the round 4-in. (10.2 cm) diameter light has a relatively high output for its size. As mentioned, by using these round lamps in multiples (gangs) it was considered possible to achieve relatively high brightness using LEDs. Therefore, the test apparatus was developed using the concept of multiple round lamps.

The initial concept was to use six units for each of the outboard assemblies and three units for the CHMSL, as shown in Figure 5. The figure shows that the upper three units in each outboard assembly were offset horizontally by half a unit so that height of the overall unit could be minimized. The on-axis illuminance output of the outboard assemblies would be approximately 1,420 cd, allowing for a 10-percent loss for the clear plastic cover over the assembly. Similarly, the on-axis output of the CHMSL would be approximately 710 cd. These values are in the same range as the Improved Alternating Pair used in the previous experiments involving incandescent lamps. Nevertheless, the brightness levels of the outboard lamp units are over 3 times greater than the maximum allowable photometric intensity levels of 420 cd for stop lamp systems, and over 10 times the minimum size as prescribed in Federal Motor Vehicle Safety Standard 108 (FMVSS 108, 2004). The CHMSL unit used in this study also has brightness levels almost 5.5 times the maximum allowable photometric intensity levels of FMVSS. Thus, the brightness levels for the LED arrays used as part of this study represent strong manipulations of this factor, and were used in order to empirically examine potential effects of the rear lighting.

Figure 5. Concept Developed for the Testing of LED Rear Lighting

To achieve the experimental setup, a full size appliqué of the rear of a vehicle was mounted to a metal backing. Lamps were then mounted in arrays in the three locations on the appliqué (for the two outboard lights and the CHMSL). Use of the appliqué concept allowed the testing of LED systems while at the same time not requiring use of an actual vehicle with its rounded rear corners. Such corners would represent a much more complex design process to embed the lamps. An additional advantage of the appliqué concept was that it allowed for the straightforward replacement of the three round CHMSL lamps by the LED TCL. Consequently, the concept could reproduce all of the desired conditions for testing LED assemblies. Figure 6 shows the actual display system using three round stop lamps as the CHMSL while Figure 7 shows the LED TCL in the CHMSL position. It should be mentioned that at distances of, say, 100 ft (30.5 m), it was difficult to tell that the experimental setup was not an actual vehicle.

Figure 6. Test Apparatus Using Three Round Stop Lamps in the CHMSL Position

Figure 7. Test Apparatus Using the LED TCL in the CHMSL Position.

Development of the Drive Electronics

Initially, two experiments were planned for the outdoor tests. The first of these was called a Frequency Optimization/TCL Pattern Selection experiment and the second was the Attention Getting/Discomfort Glare experiment. These will be described in greater detail in the following sections. In regard to the drive electronics, the frequency optimization experiment had to make it possible for the various patterns to be presented with the frequency adjustable across the entire range that might be considered optimal. This range was believed to be 2 Hz to 10 Hz, based on previous testing with incandescent lamps. The drive electronics also had to allow for the two outboard lamps to be turned on with steady output while the LED TCL patterns were presented. Since there was no straightforward way of synchronizing the flashing of the outboard lamps and the LED TCL, it was decided to use the outboard lamps at their "full-bright" output while the LED TCL was operating.

Because LEDs do not require the amount of power that incandescent lamps require, it was possible to develop a computer drive program and a solid state output module to control the two outboard lamps and the CHMSL array. The drive electronics were installed on the back side of the display "board." A confederate (experimenter) behind the board operated the computer and changed the CHMSL array from the three round lamps to the LED TCL and back again as necessary. The confederate behind the display board communicated by two-way radio with the in-vehicle experimenter seated next to a recruited participant for the study. During the actual rating process, the confederate behind the display board could not be seen by the subject.

Procedure

The subjects recruited for this study sat in the driver's seat of an automobile, parked in such a position that the eye to display board distance was initially 100 ft (30.5 m). This distance was used for the Frequency Optimization/TCL Pattern Selection Experiment and for the initial tests in the Attention-Getting/Discomfort Glare Experiment. For the latter experiment only, once tests at this distance were completed the vehicle was moved to an eye distance of 40 ft (12.2 m) for additional discomfort glare tests. Finally, the vehicle was moved to the right adjacent lane at a longitudinal eye distance of 40 ft (12.2 m) for yet another off-axis discomfort glare test. All tests were performed during daylight conditions. The in-vehicle experimenter sat in the front passenger seat, communicated by radio with the confederate experimenter behind the display board, and recorded the subject's selections of frequencies (for the flashing lamps) and pattern rankings for the LED TCL. The display board included six LED units for each outboard stop lamp assembly (one assembly on each side of the display board); all of the LED units were used with increased intensity lighting levels to represent the enhanced brake signals.

Frequency Optimization/TCL Pattern Selection Experiment

This study included 12 participants, each of whom was presented with a variety of different flash patterns and was asked to adjust the frequency for each pattern using the Method of Limits (ascending and descending trials) to determine the most desirable frequency pattern. As mentioned, the frequencies examined ranged from 2 to 10 Hz. The display allowed simultaneous flashing or alternate flashing of the lamps. The patterns used for the frequency optimization tests were as follows:

1) All lights flashing simultaneously;
2) Two outboard steady burn, CHMSL flashing;
3) Two outboard simultaneously flashing, CHMSL steady burn;
4) Two outboard alternately flashing, CHMSL steady burn; and
5) Two outboard flashing simultaneously, CHMSL alternately flashing.

In all cases the duty cycle used was 50 percent. In other words the lights were "on" for the same length of time that they were "off" for each on/off cycle.

Each participant also evaluated the selected patterns for the LED TCL. The LED TCL pattern selection process involved rank ordering the four patterns (those selected previously), as follows:

1) Pattern 4,
2) Pattern 5,
3) Pattern 10, and
4) Pattern 11 (alternating pair).

The presentation orders were counterbalanced in a combined manner. The LED TCL pattern selection procedure was considered to be one condition in the frequency optimization experiment. Thus, there were six conditions used in counterbalancing. Appendix B shows the counterbalancing scheme for the six conditions using twelve subjects.

When the LED TCL pattern ranking process was performed the subject received the four patterns in a cyclical order with entry points changed with the subjects. The patterns were repeated twice, but the subject could then request additional display of specific patterns or all patterns. The subject provided a first through fourth choice among the four, in terms of attention-getting. It should be noted that the LED TCL did not have adjustable frequency capability. Only the pattern could be varied. Therefore, this part of the experiment involved only pattern ranking. It should also be stated, however, that the manufacturer of the LED TCL had apparently chosen the patterns and frequencies to provide a high level of attention-getting.

Once the data were gathered, they were analyzed to determine the "best" frequency for each LED flash pattern and the "optimum TCL pattern." The methods used for obtaining these values are covered in the results section of this chapter. These best frequencies and the optimum LED TCL pattern were then used in the follow-on experiment, called the Attention-Getting/Discomfort Glare experiment.

Attention-Getting/Discomfort Glare Experiment

As mentioned, a separate group of participants was recruited for this study. Each subject was provided with the frequency-optimized patterns derived from the results of the first study, and was asked to rate attention-getting using an anchored scale to assign a value to each configuration. In addition, the best LED TCL pattern was used in this experiment. Figure 8 shows the scale used for quantifying attention-getting (Wierwille et al., 2003). Testing again took place while seated in the vehicle under daylight afternoon conditions. Specifically, the ratings took place on the shady side of a large four-bay garage/storage building that ran roughly north/south. Ratings for attention-getting were obtained at an eye distance of 100 ft (30.5 m) from the display board, that is, the same distance as was used in the Frequency Optimization/TCL Pattern Selection experiment. Subjects were instructed that they could rate at integral values or values half way between integral values.

Fourteen subjects were used in the experiment. They rated the attention-getting while looking directly at the display board. Immediately thereafter, they rated the discomfort glare associated with the given display using the Discomfort Glare Scale (developed by Wierwille et al., 2003), shown in Figure 9.

Visual Attention-getting Rating Scale

We would like for you to rate how attention getting this system would be when viewed against backgrounds with different levels of clutter. An uncluttered background might be one in which you are driving in a rural area with no more than one other vehicle in sight, and there are also very few billboards, traffic signals, or traffic signs. A highly cluttered background might be one in which you are driving in a congested urban area with many vehicles, traffic signals, traffic signs, and billboards. Tell the experimenter the number that most closely matches the attention-getting capability of the system (note that half values such as 2.5 are permitted).

Description	Scale	Viewer's Reaction	DEGREE OF ATTENTION GETTING
Not at all ***attention getting***	1	I would not notice this system, even against an uncluttered background.	NONE
Inconsequential level of ***attention getting***	2	I might not notice this system, even against an uncluttered background.	LITTLE BIT
Minor level of ***attention getting***	3	I would probably notice this system, but only against an uncluttered background.	
Small level of ***attention getting***	4	I would probably notice this system, but only against a relatively uncluttered background.	
Moderate level of ***attention getting***	5	I would notice this system, even against a relatively cluttered background.	A LOT
Quite ***attention getting***	6	I would notice this system, even against a cluttered background.	
Extensive level of ***attention getting***	7	I would definitely notice this system, even against a highly cluttered background.	
Extremely ***attention getting***	8	This system would get my attention under any circumstances.	FULLY

Figure 8. Attention-Getting Scale

Discomfort-Glare Rating Scale

Discomfort glare is glare that a person finds uncomfortable to a greater or lesser degree. Please rate your level of discomfort glare for this system by giving the experiment a number that most closely matches your perception of the discomfort-glare level (note that half values such as 5.5 are permitted).

DISCOMFORT GLARE LEVEL

General Description	Precise Description	Viewer's Reaction
Acceptable	**1. Not noticeable**	There is no glare with this system, and I could look at it for any length of time with no discomfort.
	2. Just noticeable	There is a small amount of glare with this system, but I could look at it for a long time without discomfort.
	3. Satisfactory	The level of glare is tolerable for this system. I could look at it for a few minutes without discomfort.
Borderline	**4. Not quite satisfactory**	The level of glare is a little bothersome. I might want to look away after a minute or two.
	5. Just acceptable	The level of glare is at the border of acceptability. I might want to look away in less than a minute.
	6. Bordering on disturbing	The level of glare is somewhat disturbing. I might want to look away in less than 30 seconds.
Undesirable	**7. Disturbing**	The level of glare is definitely disturbing. I would want to look away in less than 15 seconds.
	8. Nearly unbearable	The level of glare is nearly unbearable. I would want to look away within five seconds.
	9. Unbearable	The level of glare is definitely unbearable. I would want to look away in a second or two.

Figure 9. Discomfort-Glare Scale

Once the attention-getting ratings and discomfort glare ratings were obtained for the subject looking directly at the display, the configurations were presented again with the subject looking off angle at a standard 30 deg to the right at 100 ft (30.5 m). In this case, only attention-getting ratings were obtained. This test was intended to determine the subjective attention-getting for individuals looking away at the time that the lighting configuration was activated.

The vehicle was then moved to an eye distance of 40 ft (12.2 m) in the same lane as the display board. The configurations were presented once again and the subjects again rated the Discomfort Glare. Subjects were instructed that they could look directly at the board, but could also look away at any time if they wished. Subjects were again instructed that they could rate at integral values or values half way between integral values.

Finally, the vehicle was moved to the adjacent right lane with a longitudinal eye distance of 40 ft (12.2 m). This test was intended to determine the discomfort glare for the case in which drivers were in adjacent lanes and not likely to become involved in a rear-end crash with the lead vehicle. Once again the configurations were repeated and the subject rated discomfort glare. This completed the data gathering. Each subject was then thanked, paid, and dismissed.

A few additional details in the data gathering are worth reviewing. All ratings were obtained with the vehicle in stationary positions. The subject therefore was not driving. Runs were counterbalanced across subjects, and each counterbalance order was repeated four times for the given subject, in accordance with the rating procedures, that is, as follows:

- First presentation: On-axis attention-getting and on-axis discomfort glare at 100 ft (30.5 m);
- Second presentation: Off-axis attention-getting at 100 ft (30.5m);
- Third presentation: On-axis discomfort glare rating at 40 ft (12.2 m);
- Fourth presentation: Adjacent lane discomfort glare rating at 40 ft (12.2 m) longitudinal distance.

The procedures therefore resulted in two attention-getting ratings and three discomfort glare ratings. The counterbalancing scheme for the experiment is shown in Appendix B.

Recruitment

Twenty-six individuals were recruited to participate (12 in the Frequency Optimization/TCL Pattern Selection experiment and 14 in the Attention-Getting/Discomfort Glare experiment). Participants ranging in age from 20 to 60 were recruited using existing VTTI recruitment databases. Half of the participants were males and half were females. Potential participants were screened over the phone with a verbal questionnaire to determine whether they were licensed drivers and whether they had health concerns that might exclude them from participating in the study. Potential participants also had to be eligible for employment in the United States and must not have previously participated in similar type studies.

Initial Procedures

Each study took place on the premises of VTTI and took less than one hour. When the participant first arrived at VTTI, he or she was asked to read an Informed Consent form. After all questions were answered, the participant and experimenter both signed the form. Next the participant was asked to show a valid driver's license, then a brief vision test and an informal hearing test were administered. The hearing test was administered to ensure that the participant would be able to hear the experimenter's verbal instructions while in the vehicle and consisted of the participant repeating four sentences back to the experimenter. A Snellen vision test was administered to ensure that visual acuity was within the legal driving limit (corrected to 20/40). The Ishira Color Vision test was also administered. The experimenter recorded the participant's ability to detect color, but results were not part of the eligibility criteria. The participant was then escorted to the parked study vehicle following these tests. As mentioned, all experiments were performed in a static field testing arrangement.

Analysis and Results

Frequency Optimization/TCL Pattern Selection Experiment

Optimum Flashing Frequency as a Function of Pattern

Reviewing, there were five flashing patterns used in the Frequency Optimization portion of the first experiment, as follows:

1) All lights flashing simultaneously;
2) Two outboard steady burn, CHMSL flashing;
3) Two outboard simultaneously flashing, CHMSL steady burn;
4) Two outboard alternately flashing, CHMSL steady burn; and
5) Two outboard flashing simultaneously, CHMSL alternately flashing.

Frequency optimization therefore involved an array of five conditions by 12 frequency values, that is, one for each subject and each condition. A one-way-within-subjects analysis of variance with frequency value as the dependent variable and flashing pattern as the independent variable failed to reach statistical significance, $F(4,55) = 1.65$, $p = 0.173$. Additional nonparametric tests were also run, but did not result in significance. Figure 10 shows the mean, median, and mode for each of the flashing configurations. Standard error bars are shown for the means. Note that differences in the mean values are not significant.

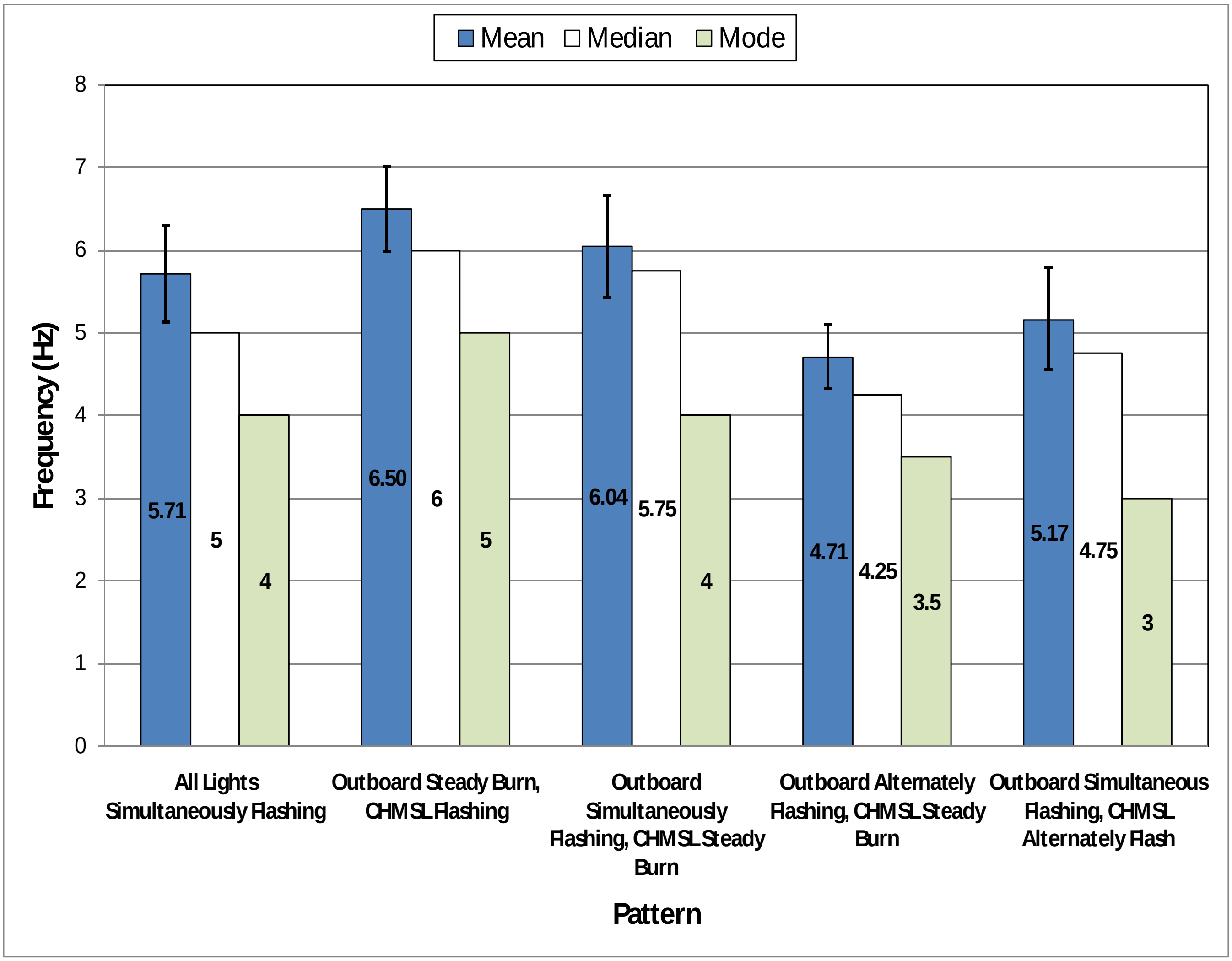

Figure 10. Graphical Results for the Frequency Optimization Experiment (Differences in Means Are Not Significant)

To select "the optimum frequency" for each pattern, it is first desirable to recognize that all values for the mean and median fall between 4.25 and 6.5 Hz. Because of the closeness of these values, it is not surprising that differences failed to reach significance. Nevertheless, it seems prudent to use the best estimate of mean or median for each individual pattern, based primarily on statistical concepts that state that both the sample mean and median are unbiased estimators of the population mean. On the other hand, it should be recognized that the median value will have a tendency to suppress outliers because subjects rating at very high or very low values will not be able to heavily bias the results, even though the sample mean is more efficient (in a statistical sense). The mean value on the other hand will give outliers full weight, suggesting that outliers may heavily influence the results in a small sample. While arbitrary to some extent, it seems that the median value for each pattern should be used as "the optimum frequency." Consequently, the middle bar for each pattern in Figure 10 is the recommended optimum frequency. These frequency values are given within the bar.

LED TCL Pattern Selection

Four patterns were evaluated by the subjects in the first experiment. These were

1) Pattern 4,
2) Pattern 5,
3) Pattern 10, and
4) Pattern 11 (alternating pair).

The subjects rank ordered the patterns in terms of attention-getting. They did not, however, rate the four patterns *individually* in terms of attention-getting. A Friedman nonparametric test was run on the rankings (four rankings by 12 subjects). Because subjects were *required* to rank order the four patterns, there were no ties. The Friedman test did not result in significance ($\chi^2 = 4.10$, $p = 0.251$).

Because there was no clear-cut winner in the rank ordering, another procedure was used to make a selection. Each time a given pattern received a top ranking by a subject, it was assigned a value of 1. Each time a given pattern received a second place ranking it was assigned a value of 2. For third place the assigned value was 3, and for fourth place the assigned value was 4. The assigned values were then summed across subjects. Figure 11 shows the results.

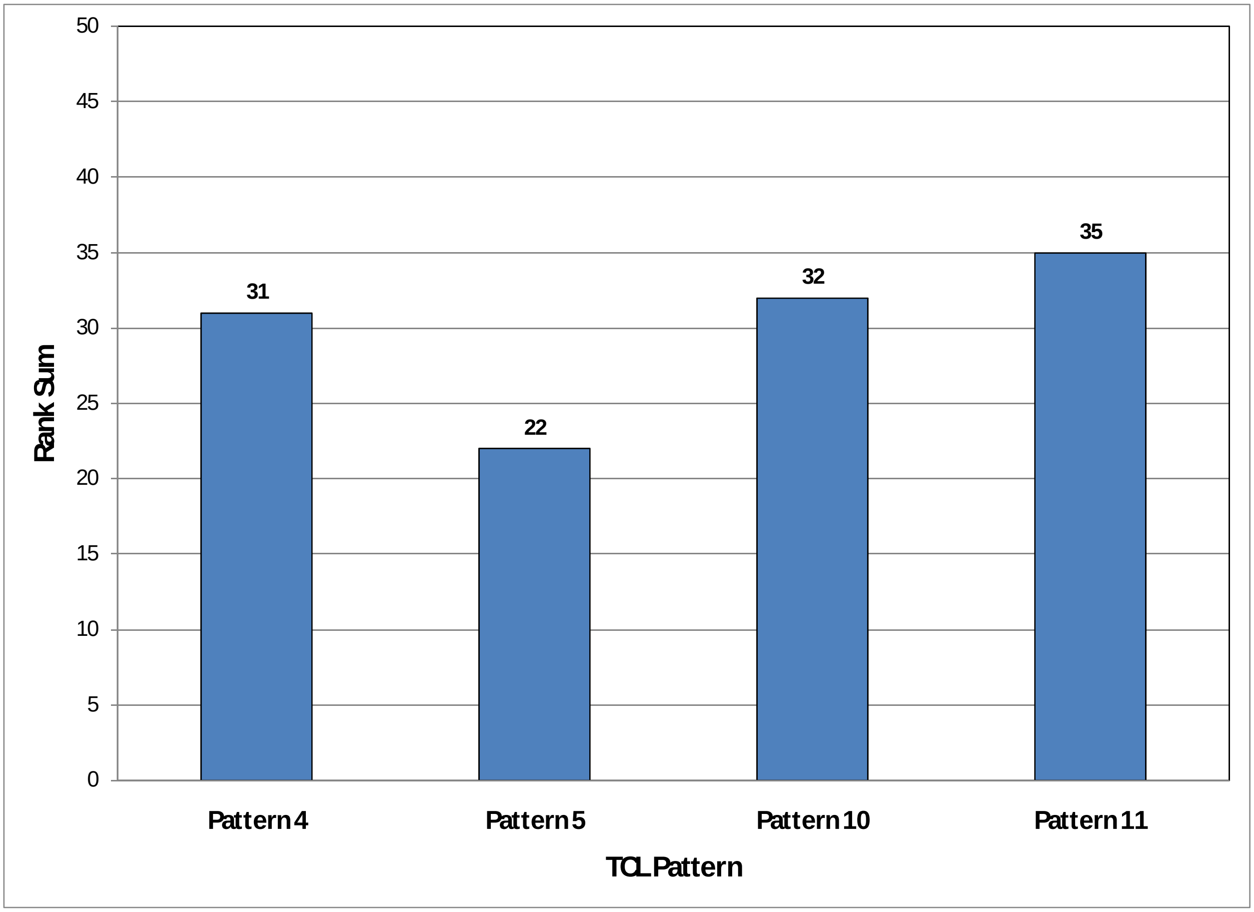

Figure 11. Summed Rankings as a Function of LED TCL Pattern

The results show that Pattern 5 ranked substantially lower (that is, better) on average than the other patterns, and therefore was the pattern recommended for use in the follow up attention-getting/discomfort glare experiment. It should also be mentioned that Pattern 5 received 50percentpercent of the first place rankings, the highest value. The next highest first place ranking went to Pattern 11 with 33 percent of the first place rankings.

The method used to obtain this optimum is arbitrary to an extent, in that rankings by drivers are not necessarily equally spaced. However, the procedure does account for first-place rankings and for all rankings as well, although the weighting is arbitrary. In the absence of additional information and statistical significance, this procedure seems as good as any.

Pattern 5, the selected pattern, will now be described in greater detail. The pattern is depicted in Figure 12. The two outer triangles were flashed three times, with dark intervals in between (part A in the figure). Then the inner triangle was flashed three times (part B in the figure), with dark intervals in between. Thereafter, this overall pattern was repeated. Duration of the overall pattern was estimated at 1.0 s; therefore, each "on" segment was approximately 83.3 ms and each "off" segment was approximately 83.3 ms. In all, there were 12 segments, both on and off, that produced the 83.3 ms value per segment.

It is worth noting that the LED TCL (Pattern 5) produces approximately 6 flashes per second. This value is in the range of results obtained for the other configurations in the frequency optimization experiment

	On	Off	Repeated	Duration (estimate)
Part A			3x	0.5s
Part B			3x	0.5s

Figure 12. Pattern 5 of the LED TCL Sequence

<u>Attention-Getting/Discomfort Glare Experiment</u>

As described earlier, there were two ratings of attention-getting and three ratings of discomfort glare for each of seven configurations. Each rating condition was analyzed separately.

The attention-getting ratings at 100 ft (30.5 m) were examined using a one-way-within-subjects ANOVA with pattern as the independent variable. The results were significant with $F(6,91) = 5.82$, $p < 0.0001$. Figure 13 shows a plot of the means with SNK post hoc test results. Means having a common letter are not significantly different from one another ($\alpha = 0.05$).

These results indicate that the first two patterns (on the left in the figure) are significantly different from the last two patterns (on the right). Clearly, the steady burn and flashing CHMSL with steady outboard burn are not as good as the first two, that is, outboard simultaneous flashing with CHMSL alternating flashing, and all simultaneously flashing. It appears that flashing and pattern size affect the results.

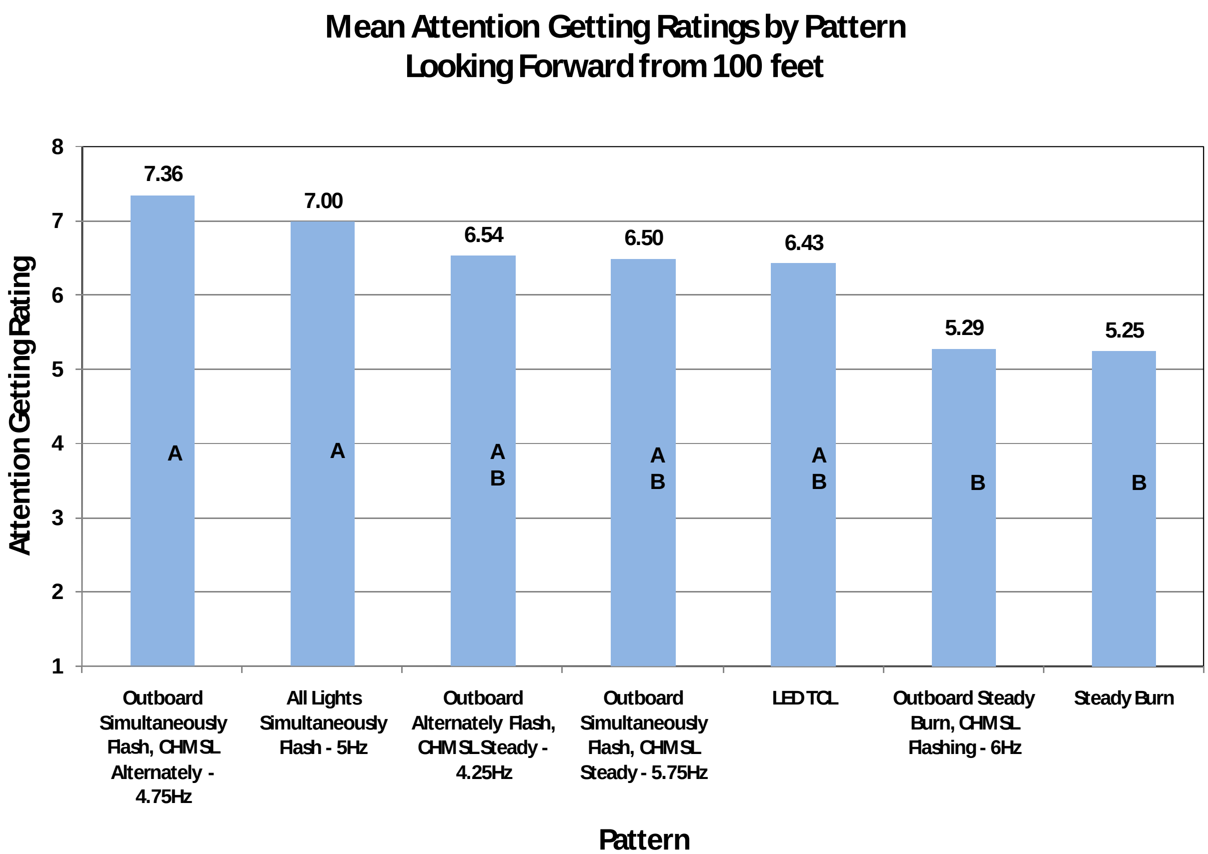

Figure 13. Results of the Attention-Getting Ratings at 100 ft (30.5 m) Looking Directly Forward

When looking 30 deg to the right small differences in ordering occur (Figure 14). First of all, the one-way-within-subjects ANOVA is significant $F(6, 90) = 15.45$, $p < 0.0001$. However, in this case, the SNK post hoc tests show that the first four configurations (on the left in the figure) are significantly different from the three on the right. In addition the third pattern from the right is significantly different from the pattern on the right. These results suggest that the flashing of the outboard lamps is important to off-axis attention-getting. Note that the three patterns on the right do not flash the outboard lamps.

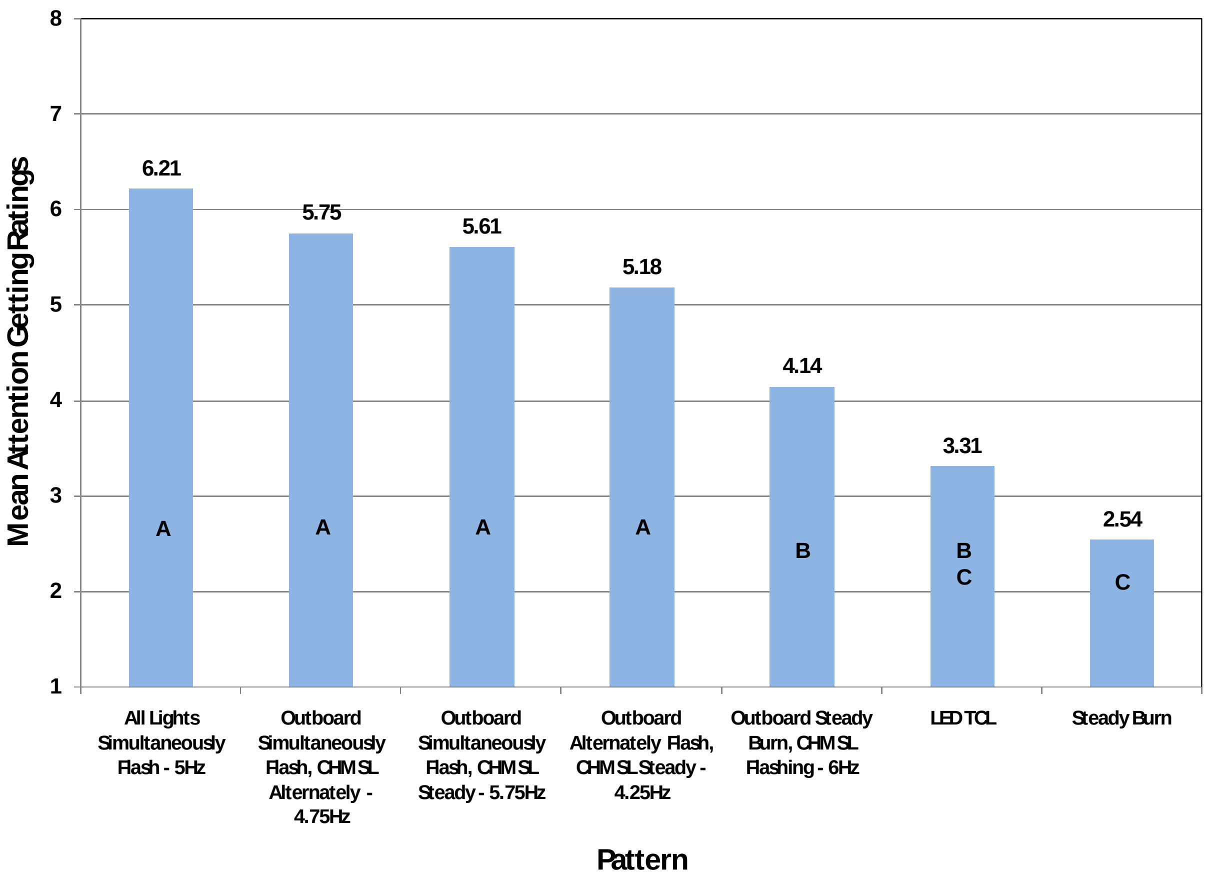

Figure 14. Results of the Attention-Getting Ratings at 100 ft (30.5 m) Looking to the Right 30 Deg Off Axis

Figures 13 and 14 show that the strongest candidates are:

- All lights simultaneously flashing, 5.0 Hz;
- Outboard simultaneously flashing, CHMSL alternately flashing, 4.75 Hz.

These two candidates are first and second in both attention-getting ratings data sets.

Other candidates showing good results are:

- Outboard simultaneously flashing, 5.75 Hz, CHMSL steady;
- Outboard alternately flashing, 4.25 Hz, CHMSL steady.

Note specifically that neither the LED TCL nor the steady burn outboard conditions does consistently as well as the above four conditions.

The above four configurations have a grand mean value of 6.85 when looking forward from 100 ft (30.5 m), and a grand mean of 5.69 when looking away to the right at 100 ft (30.5 m). These values correspond to "quite to extensive attention-getting" for the 6.85 value, and "moderate to quite attention-getting" for the 5.69 value.

Discomfort Glare Ratings

The first discomfort glare ratings were taken at the 100 ft (30.5 m) distance with subjects looking straight ahead. A one-way-within-subjects ANOVA revealed significance with $F(6, 91) = 3.63$, $p = 0.0029$ (Figure 15). Post hoc SNK tests showed that the first five patterns (on the left in the figure) differed significantly from the pattern on the right. The results show that by and large the attention-getting ratings of the patterns and the discomfort glare ratings are similarly ordered, with minor exceptions.

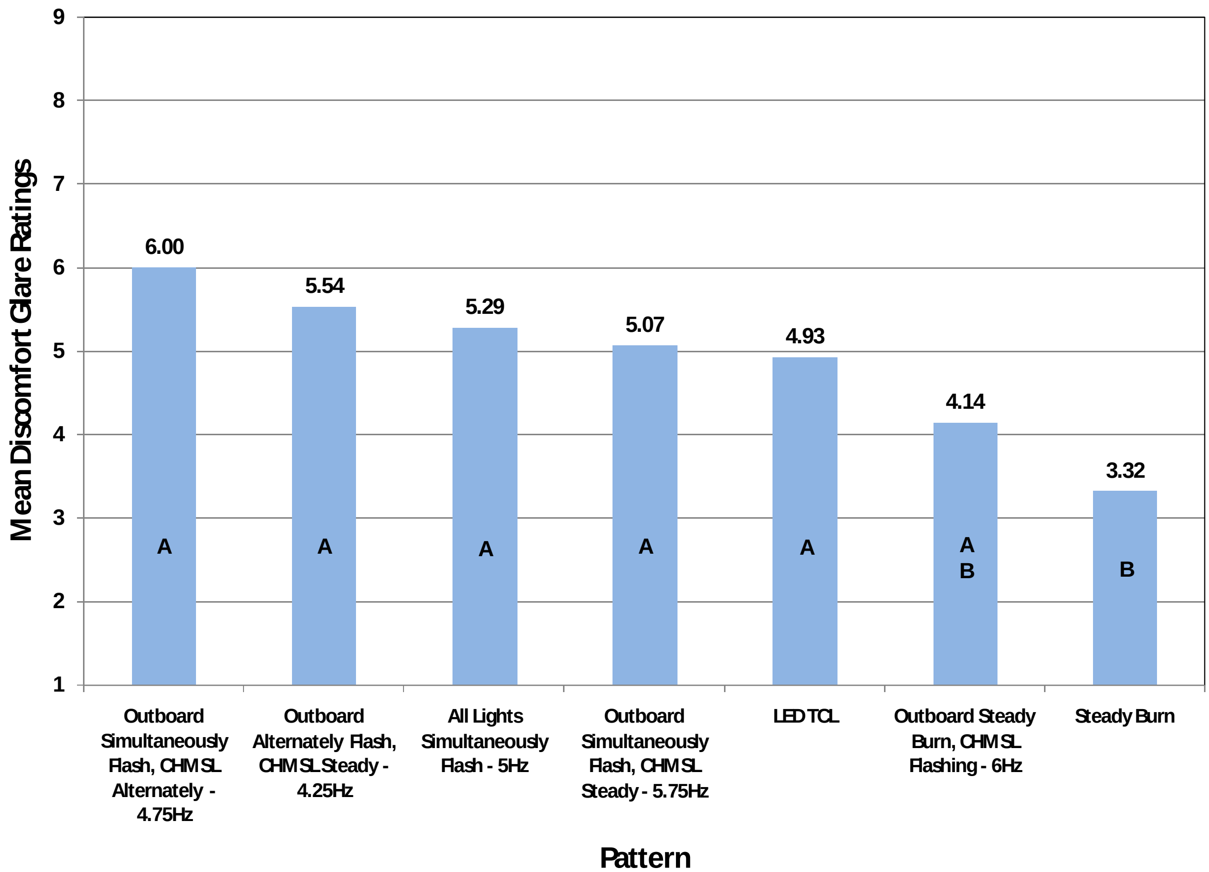

Figure 15. Results of the Discomfort Glare Ratings at 100 ft (30.5 m) Looking Directly Forward

Discomfort glare ratings were similarly taken at 40 ft (12.2 m). This distance was used to test how uncomfortable drivers might feel at typical following distances in traffic, should the enhanced rear lighting signal activate or remain on after an emergency. As before, the ratings results were tested using a one-way-within-subjects ANOVA. Results indicated significance with $F(6,91) = 4.62$, $p = 0.0004$ (Figure 16). Post hoc SNK tests revealed that the first four configurations on the left in the figure differed significantly from the steady burn condition shown on the right. Here again, it becomes clear that there is a strong relationship between attention-getting and discomfort glare. The ratings in Figure 16 are ordered quite similar to the attention-getting ratings.

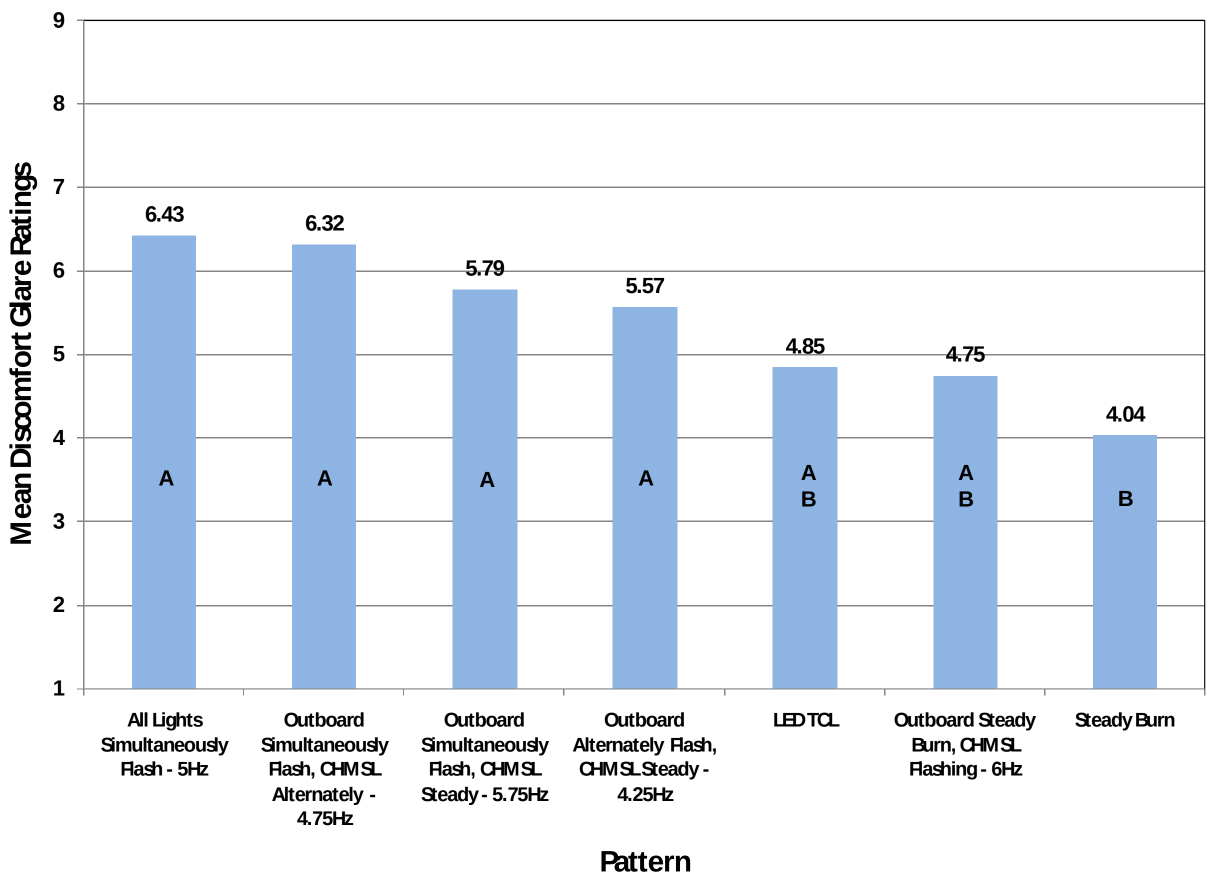

Figure 16. Results of the Discomfort Glare Ratings at 40 ft (12.2 m) Looking Directly Forward

For the four configurations having the best attention-getting capability, the grand means for discomfort glare at 100 ft (30.5 m) and at 40 ft (12.2 m) were 5.46 and 6.03 respectively. As expected the glare would be greater at the closer distance. At the 100 ft (30.5 m) distance the mean value corresponds to the point between "just acceptable and bordering on disturbing" with desire to look away after approximately 45 seconds. At the 40 ft (12.2 m) distance the mean value corresponds to "bordering on disturbing" and wanting to look away after perhaps 30 seconds. These values would probably be considered tolerable because the enhanced rear lighting signal would not be expected to last more than, say, 6 s. Of course, these are daytime values. At night, no doubt, the lamps would need to be attenuated.

Discomfort glare ratings were also obtained in the adjacent lane at a longitudinal distance of 40 ft (12.2 m). Drivers were instructed to look forward when deciding upon their ratings. In other words, they were instructed to look "past" the vehicle applique display, as if looking at a vehicle directly in front of them. The ratings were intended to assess the distraction effect to drivers in the adjacent lane, who would not likely be involved in a rear-end emergency or collision with an equipped vehicle. As before, the ratings were initially subjected to a one-way-within-subjects ANOVA with configuration as the independent variable. Results were significant, $F(6, 86) = 2.52$, $p = 0.0269$. However, post hoc tests did not demonstrate any significance between conditions. Both SNK and Tukey's HSD tests were applied, and both failed to demonstrate significance. The results are shown in Figure 17.

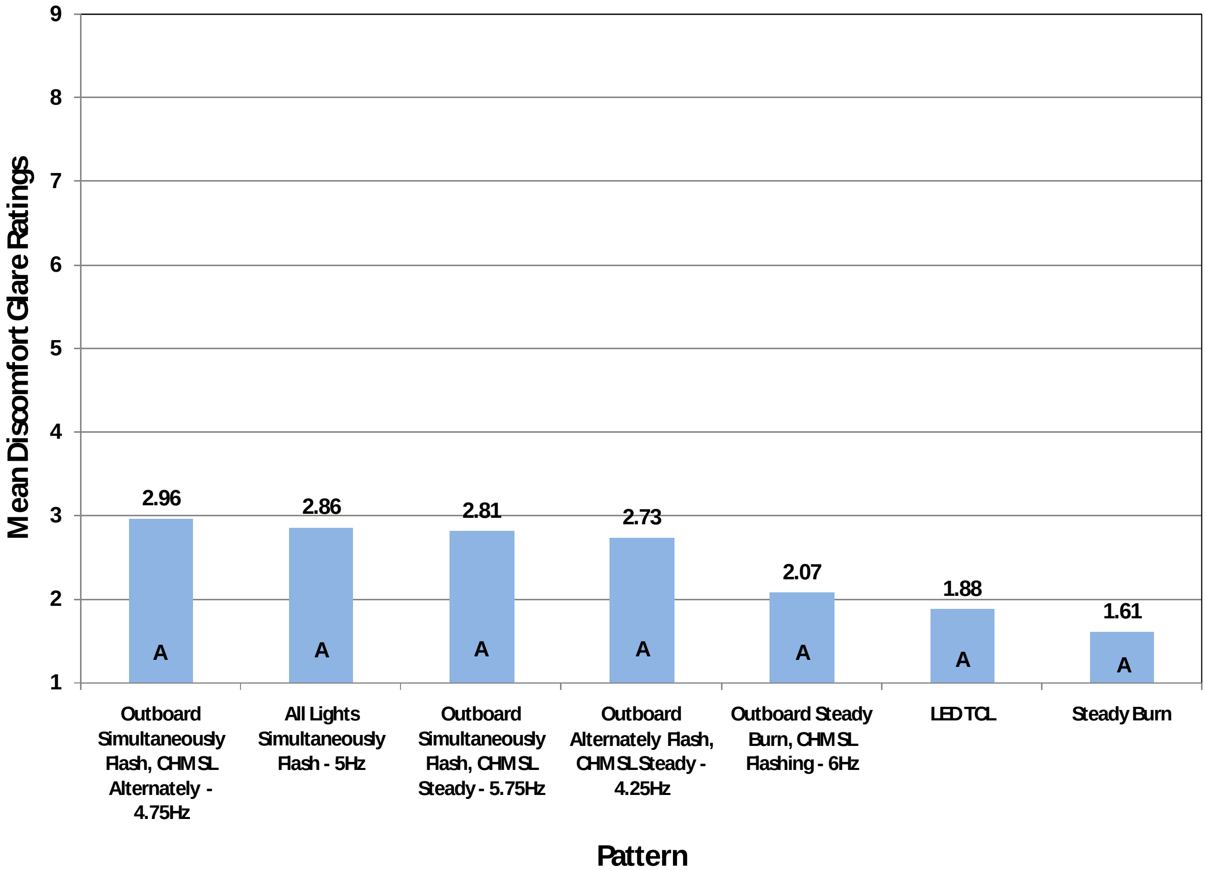

Figure 17. Results of the Discomfort Glare Ratings at 40 ft (12.2 m), Longitudinal, in the Right Adjacent Lane Looking Straight Forward

The figure shows that all of the mean discomfort glare ratings are relatively low, ranging from 2.96 to 1.61. These results suggest that discomfort glare to drivers in adjacent lanes is not a problem. A value of 3.0 corresponds to satisfactory or tolerable. A value of 2.0 corresponds to "just noticeable." The much lower values can be attributed to the relatively narrow beamwidth of 7 deg, as shown earlier for an individual round taillight assembly.

Conclusions

The studies performed have been quite revealing. Taken together, they give a relatively complete picture of what can be expected with LED rear enhanced braking signals. Various points are made in this section that are largely a result of the entire study, not just specific results.

- One important finding is that the optimum flash frequencies for LED enhanced rear lighting are slightly higher than for incandescent lamps. In incandescent lamps there appears to be a tradeoff between flash frequency, and rise and fall times of the light output. An incandescent lamp might reach full output in perhaps 50 ms and would extinguish in perhaps 150 ms. On the other hand LED lamps might reach full output in 2 ms and would extinguish in perhaps 4 ms. To the human observer, LED lamps appear to light and extinguish instantaneously. On the other hand, a human observer can see the lag in incandescent lamp extinguishing and would no doubt call both onset and extinguishing much smoother. Now, as the frequency increases, the attention-getting for incandescent lamps becomes a tradeoff between flashing and smoothing, whereas for LED lamps there is no such tradeoff. For incandescent lamps, the flashes begin to run together. Consequently, there are two aspects of LED lamps that are different. The optimum flash frequency may have greater variance and the median frequency may be higher. Both of these aspects were observed in the present experiments. Earlier incandescent lamp experiments found 4.0 Hz to be optimum, and there was tight clustering around this value (Wierwille, Lee, & DeHart, 2005). The current experiments found mean/median values of 4.25 to 6.5 Hz, and there was sufficient variance that significant differences did not exist among the configurations in terms of the frequency. This result occurred even though there was a fairly good sample size.

- It appears that present-day LED lamps are capable of competing with incandescent lamps in terms of attention-getting. However, in the present study, this was accomplished by using multiple units or assemblies along with narrow beamwidths that emit light in excess of current permissible levels. In the current experiments, each outboard lamp was composed of six round, high-output units, and the CHMSL was composed of three such units. Future experiments should make the comparisons between the two technologies clearer. Whether or not present-day LED technology can compete with "best" previous incandescent technology will be studied in the follow-on experiments. These best technologies include the incandescent TCL and the incandescent Improved Alternating Pair (Wierwille, Lee, & DeHart, 2005). However, based on the experiments already reported, it can be said that LED tail lamp assemblies appear promising in terms of providing enhanced rear lighting signals to following drivers. There is an obvious trend in automotive design toward LED applications, because these lamps use lower currents and therefore have greater electrical efficiency. Consequently, new enhanced rear warning systems research should use LED technology if possible.

- Flashing improves rated attention-getting. The experiments show that for LED technology flashing increases the ratings obtained. This result is in agreement with earlier experiments that showed that flashing increased the attention-getting ratings for incandescent lamps, as compared with steady lamps (Wierwille, Lee, & DeHart, 2003). In addition, the LED experiments show that "wider is better." In other words, flashing the outboard lamps produces greater rated attention-getting than other flashing arrangements. Of course, in the current experiments, the outboard lamps had substantially greater total light output than the CHMSL and therefore it is not unreasonable to expect that flashing these outboard lamps would produce a greater effect. In general, it can be said that flashing is beneficial in terms of rated attention-getting and bright flashing of the outboard lamps are even more beneficial.

- Rated discomfort glare is closely related to rated attention-getting. It appears that it is necessary to accept somewhat greater rated discomfort glare to achieve greater attention-getting. Here again, the result is the same as for earlier tests with incandescent lamps, which showed a near-identical ordering for discomfort glare and attention-getting for various enhanced rear lighting systems.

- For LED lamps evaluated in this study (which had narrow beam widths), rated discomfort glare was found to be lower in adjacent lanes than that of incandescent lamps. To achieve necessary brightness levels using LEDs, beamwidths must be relatively narrow. One beneficial consequence is that light energy is much more concentrated in the lane directly behind the equipped vehicle. Of course, this is the lane from which a following rear-end crash vehicle is likely to approach. Vehicles approaching in adjacent lanes are not likely to have a rear-end collision with an equipped vehicle because a lane change would almost universally be required to do so. If a lane change (to the same lane) by the following vehicle does occur, then the enhanced rear lighting would become effective. Thus, the LED lamps evaluated in this study have the advantage that discomfort glare for drivers in adjacent lanes would be lower, a desirable characteristic. Note that comparable narrow beam patterns may also be achieved using incandescent lamps.

- The LED TCL was not among the best finalists for rated attention-getting. This finding is believed to be a result of the fact that the configuration in which it was used did not include flashing of the outboard lamps. The LED TCL is a complicated device and could be replaced by a simpler flashing CHMSL with the same effectiveness.

- The best configurations for future testing therefore appear to be those in which the outboard lamps flash, either alternately or simultaneously. Among those tested in the current experiments, the two most recommended are the following:

  1. Outboard lamps simultaneously flashing, CHMSL alternately flashing at 4.75 Hz, and
  2. All lights simultaneously flashing at 5.0 Hz.

  Two additional configurations that should be effective are the following:

  1. Outboard lamps simultaneously flashing at 5.75 Hz, CHMSL steady.
  2. Outboard lamps alternately flashing at 4.25 Hz, CHMSL steady.

- Finally, it can be said that the planned experiments provided useful results and reached the intended objectives.

Chapter 3. Additional Static Evaluation of Previously Optimized and Previously Proposed Enhanced Rear Lighting Signal Candidates

Study Purpose & Objectives

The purpose of this study was to determine how well previously optimized LED arrays of present-day lighting configurations compete with other lighting configurations, including the incandescent Traffic Clearing Lamp. The incandescent TCL was found to provide the best overall performance (attention-getting capability and response time) in previous studies at VTTI (Wierwille, Lee, & DeHart, 2005). Also included were other enhanced rear lighting approaches, some of which were patterned after manufacturers' concepts, but using frequencies determined to be optimum in previous studies performed under the current contract. The study was directed at quantifying the attention-getting capability and discomfort glare of a set of candidate test configurations using driver judgments, as well as eye-drawing metrics of a subset of configurations using an uninformed detection event methodology. This study served as yet another form of refinement to the planned on-road study by helping to select and optimize the set of candidate lighting configurations to be implemented in a research vehicle.

Study Design

Evaluations conducted as part of this study closely resembled the procedures and methods used in the previous Attention-Getting study conducted as part of this series. Testing was performed with a group of naïve drivers (no previous exposure to the lighting arrays) under static conditions (parked vehicle with individuals not driving the vehicle). Twenty-seven participants were exposed to the full set of lighting configurations (nine listed below); each participant was asked to make a series of judgments related to attention-getting and discomfort glare using the same anchored rating scales used in earlier studies, as well as evaluations of a new measure: effective intensity. As in the previous attention-getting study, each participant made several judgments obtained under a variety of conditions; different viewing distances, 100 ft (30.5 m) and 40 ft(12.2 m), lane positions (directly behind the equipped vehicle and in the adjacent lane), and viewing angles (straight-on, and off-angle). This study served to replicate the previous Attention-Getting study, but with a different group of rear lighting configurations. The goal was to further reduce the set of candidate lighting configurations to those that would most likely be carried forward to the on-road study.

Uninformed Event Detection Paradigm

Unlike previous work under the current contract, initial uninformed lighting event detection trials (administered before drivers were informed about the true purpose of the study) were used to assess eye-drawing capability for a subset of the lighting configurations (lighting configurations for these uninformed trials were treated as a between-subjects factor). The uninformed event trials were intended to supplement the usual subjective ratings with performance-based values (time to draw eyes to the forward view when otherwise occupied). During these early trials, participants (seated in the driver's seat) were asked to complete in-vehicle tasks using an in-car navigation system that caused them to direct their gaze away from the forward roadway. The display and controls were located at a nominal horizontal angle of 30 degrees to the right of the straight forward glance position and then vertically downward at a nominal angle of 18 degrees. Another way of describing the position of the navigation system was that it was located along the vehicle centerline, to the right of the steering wheel, near the top of the instrument panel (Figure 18).

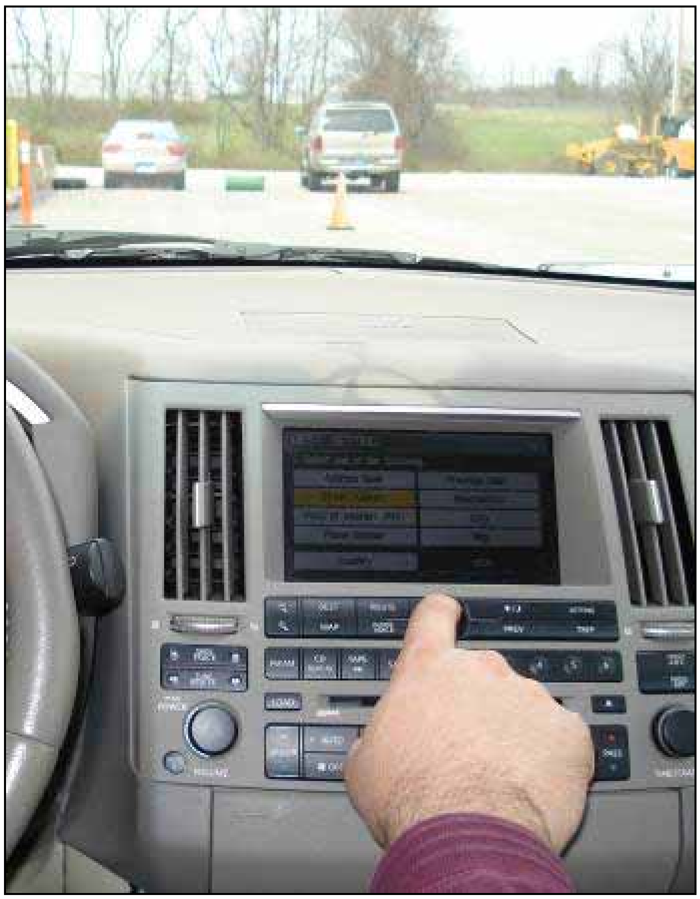

Figure 18. Navigation System in the Vehicle Used for the Uninformed Event Detection Trials

Once the driver was engaged in the navigation task (looking away from the forward view) the in-vehicle experimenter gave a signal to activate the lighting array. This was accomplished by having the in-vehicle experimenter signal the confederate experimenter behind the display board (vehicle appliqué concept described previously) using a transmitted radio tone. Care was taken to ensure that the participant did not detect that the experimenter sent the tone. The rear lighting display (vehicle appliqué concept) was straight ahead at a nominal eye to display distance of 100 ft (30.5 m).

In all, there were three triggering events for each participant, all of which occurred without informing the participant. These triggering events occurred as follows: once while receiving instruction but looking at the navigation system display, once when selecting among menu items in the navigation system, and once during text entry into the navigation system. These three events were chosen to reflect increasing levels of visual, cognitive, and manual loading. The number of occurrences of eye-drawing (participants looking up) and the times it took them to redirect their gaze forward were measured and served as key dependent measures for assessing eye-drawing capability. Note that obtaining these measures required that a data acquisition system be used to capture time-synchronized video of the participant's (driver's) eye position and the state of the lead vehicle's brake lamps. Although participants did not drive the vehicle during the navigation task elements (and therefore had no need to look forward), the hypothesis was that effective signals would compel individuals to redirect their gaze forward. In other words, the eye-drawing capability of some of the signals would cause the driver to look forward even though the need to look forward (as if driving) was not present. Preliminary work was conducted in selecting the navigation tasks to ensure the effectiveness of the approach. Measures of eye-drawing capability (i.e., whether or not drivers looked forward in response to the signal activations and latency of looking forward) were used in conjunction with the subjective evaluations of the entire set of available lighting configurations (obtained later) to narrow the pool of candidate signals.

In all, five different rear lighting configurations were tested using the uninformed event detection paradigm. Eighty drivers (that is, all of the subjects) participated in the uninformed event detection paradigm. This number was considered to be large, but was necessary because of the between-subjects design. There were 16 drivers per display condition. The use of a between-subjects design was considered necessary because re-exposure, after informing participants of the ruse, would not have provided the surprise (uninformed event) effect that was a goal of the experiment.

Remainder of the experiment design (Ratings Experiment***)***

Although there were 80 total participants in this experiment, only 27 of the first 40 continued to complete all of the further evaluations of rear lighting. The reason for using these unequal numbers was that the use of 27 participants was considered sufficient to test a group of nine different rear lighting configurations using a totally within-subjects design, whereas 80 were required (16 per condition) to obtain sufficient statistical power for the between-subjects design associated with the uninformed event detection experiment. Fifty-three (that is, 13 in the initial group of 40 and the entire second group of 40) were dismissed after completing the uninformed event detection trials. Of course, all participants were debriefed regarding the ruse as soon as it was completed. In summary, all 80 participants completed the uninformed event detection paradigm part of the experiment, and 27 of the first 40 participants performed all of the rear lighting tasks including the uninformed event detection paradigm part. Figure 19 depicts these aspects of the experimental design.

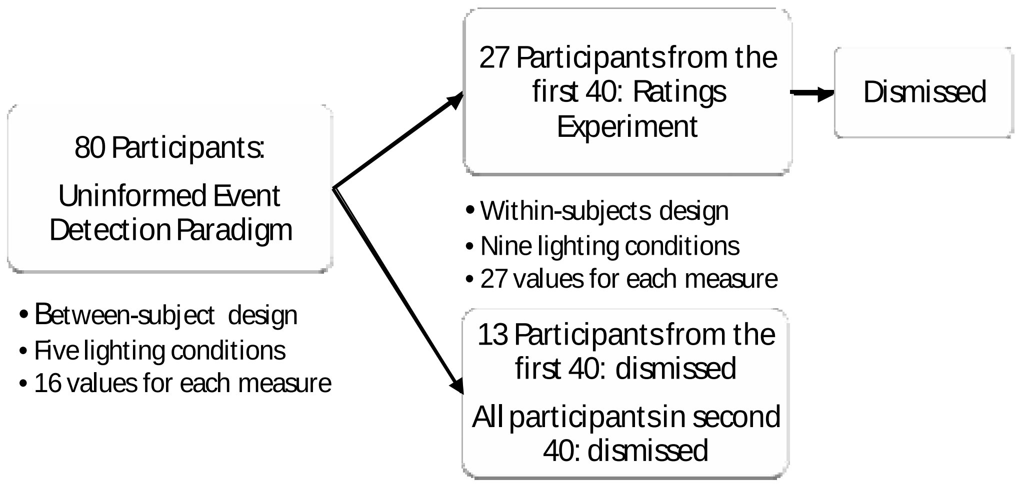

Figure 19. Study Design for the Uninformed Event Detection Paradigm and the Subsequent Ratings Experiment

It should be mentioned that the use of 27 participants in the ratings portion of the experiment was dictated by the need for partial counterbalancing (along with the consideration of adequate statistical power). At the same time, there was a need to ensure that all five brake lighting configurations used in the Uninformed Event Detection trials were treated equally in terms of time of day and weather conditions. Consequently, rear signal lighting conditions for the five were selected to minimize the influence of these environmental effects.

<u>Brake Lighting Configurations & Test Conditions</u>

Nine rear signal lighting configurations were evaluated via ratings. These are summarized as follows:

1. Traffic Clearing Lamp (incandescent) combined with outboard lamps at increased brightness,
2. Simultaneous Flashing of All Lamps With Increased Brightness, optimized in frequency according to previous experiments under the current project,
3. Simultaneous Flashing of All Lamps With No Increase in Brightness (sometimes referred to as a Mercedes-Benz-type signal), optimized in frequency according to previous experiments under the current contract,
4. Increased Lamp Intensity (sometimes referred to as a Volvo-type signal),
5. Enlarged Brake Lamp Area and Increased Brightness (sometimes referred to as a BMW-like signal),

6. Outboard Alternating Flashing, CHMSL Steady (alternating pair, outboard), optimized in frequency according to previous experiments under the current project,
7. Outboard Simultaneously Flashing, CHMSL Alternately Flashing, optimized in frequency according to previous experiments under the current project,
8. Two CHMSL Lamps Alternately Flashing, Outboard Steady (alternating pair, CHMSL), optimized in frequency according to previous experiments under the current contract, and
9. Baseline (conventional, steady burn).

Among these, 1, 2, 3, 7, and 9 were selected for the uninformed event detection trials. Table 5 describes each configuration in greater detail. Note that all concepts, with exception of the incandescent TCL, were implemented with LED technology; this provided a fairer comparison among signal approaches and was believed likely to be more representative of industry trends. The TCL (in incandescent form) was retained because the solid state equivalent did not show as much promise in earlier experiments under the current contract (Chapter 2). The five highlighted configurations in Table 5 were used during the uninformed event detection trials (with 16 drivers per condition, as previously stated); this includes comparisons among four enhanced signal concepts and a baseline condition, that is, five signals in all. Of course, all nine configurations were used for the ratings portion of the study that followed (for 27 of the participants).

Testing employed a two-stage approach in presenting each rear signal. The first level (or interval) represented nominal braking levels (characteristic of current steady brake lighting levels) and lasted for 1s. The second level represented the enhanced rear lighting condition and lasted for 5 s; increased intensity lighting levels were used during this second interval . Consequently, rear lights were on for a total period of 6 s (the enhanced rear lighting signal followed the nominal level without a break in the lighting, that is, continuously). In regard to condition 9, the baseline condition, the first level of brake lighting was simply extended for 5s. This of course resulted in a signal of the same total time length, that is, 6s.

It should be mentioned that use of the incandescent TCL required construction of yet another CHMSL assembly. In this assembly, two round 40-LED lamps were used with a single TCL module placed between them, as shown in Figure 20. This assembly was used solely for signal lighting configuration 1, in which the two LED lamps were illuminated during the initial 1 s of normal braking and the TCL (without the two LED lamps) was energized during the enhanced rear lighting portion. It is important to remember that all of the other configurations (2 through 9) used the CHMSL composed of three 40-LED lamps (Figures 5 and 6 of Chapter 2).

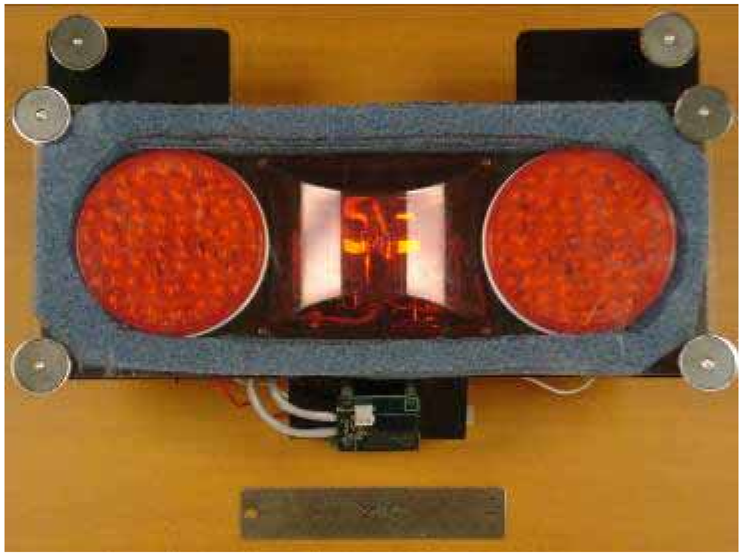

Figure 20. CHMSL Assembly Including the Center Incandescent TCL With Side LED Lamps

Table 5. List and Description of Brake Signal Configurations - Highlighted Configurations Were Evaluated as a Between-Subjects Factor During the Uninformed Event Detection Experiment

	Brake Lamp Configurations	Short Title	Notes
1	Traffic Clearing Lamp Incandescent Incandescent TCL (electro-mechanical unit) used in previous work Paired with LED lamps (TCL in center CHMSL position) Brake lighting: All lamps (including CHMSL LED lamps) normal illumination level (TCL not activated). Enhanced rear lighting lighting: TCL activated with outboard LED lamps full output (No CHMSL LEDs activated, TCL only)	Incandescent TCL,	Top performer in previous research performed at VTTI, including test track study. Also serves as benchmark allowing results of this study to be compared to test-track work (enables initial validation of alternate configurations using LEDs)
2	CHMSL Alternating Flash, Outboard Steady (Alternating Pair, CHMSL) LED Implementation Brake lighting: All LED lamps(including CHMSL with three LED lamps) normal illumination level Enhanced rear lighting: Two outboard CHMSL LED lamps flash at 4.25 Hz and at high brightness with center CHMSL lamp off; outboard lamps at brake level brightness, steady burn.	CHMSL Alt. Pair, Steady Outboard	LED illumination levels for brake lighting to be matched to OEM LED levels. Serves as standard brake lighting level for nearly all configurations This configuration is similar in concept to configuration #6 (Alternate Pair, Outboard)
3	Increased Lamp Intensity (All Lamps Increased Brightness) LED implementation	Increased Intensity	No flashing Brightness increase only Sometimes referred to as the

	Brake lighting: All lamps (including CHMSL with three LED lamps) normal illumination level Enhanced rear lighting: All lamps full output brightness		Volvo approach
4	Optimized Simultaneous Flashing Of All Lamps (Increased Brightness) LED Implementation All lamps simultaneous flash @ 5.0 Hz Brake lighting: All lamps (including CHMSL with three LED lamps) normal illumination level (matched to OEM LED level), no flashing Enhanced rear lighting: All lamps flashing at 5.0 Hz with full output brightness level	Simultaneous Flash (Increased Brightness), or Flashing w/ Increase	Top rated attention-getting configuration in LED Optimization study. Same as #3, but increase in brightness levels Flash rate optimized to configuration
5	Enlarged Brake Lamp Area & Increased Brightness LED implementation Concept combines increased area and brightness Brake lighting: Center LED lamp in CHMSL and lower two inside LED lamps in outboard lamp assemblies at normal illumination level (brightness matched to OEM LED level). Enhanced rear lighting: All lamps full output brightness	Enlarged Area & Intensity	Effect of increased area alone determined by comparison to configuration #4 BMW-like concept (increased area), but adds increased brightness (resembling likely implementation approach)
6	Optimized Simultaneous Flashing Of All Lamps (No Brightness Increase) LED Implementation All lamps simultaneous flash @5.0 Hz Brake lighting: All lamps (including CHMSL with three LED lamps) normal illumination level (matched to OEM LED level), no flashing Enhanced rear lighting: All lamps flashing at 5.0 Hz with same brightness level as brake lighting	Simultaneous Flash (No Increase), or Flashing w/out Increase	Same as #2, but no increase in brightness levels Comparison to configuration #2 of practical significance to OEMs. Flash rate optimized to configuration Sometimes referred to as the Mercedes-Benz approach
7	Outboard Simultaneously Flash, CHMSL Alternately Flash LED Implementation Brake lighting: All lamps (including CHMSL with three LED lamps) normal illumination level Enhanced rear lighting: Full brightness output to all lamps. CHMSL flashing alternately with outboard lamps @4.75 Hz	Outboard Simultaneously Flash, CHMSL Alt.	Among top rated attention-getting configurations in LED Optimization study. Flash rate optimized to configuration
8	Outboard Alternating Flash, CHMSL Steady (Alternating Pair, Outboard) LED Implementation Brake lighting: All lamps normal illumination level Warning lighting: Full output brightness to all lamps, CHMSL steady, Outboard alternately flash @4.25 Hz	Outboard Alt. Pair, CHMSL Steady	Among top rated attention-getting configurations in LED Optimization study. Flash rate optimized to configuration
9	Baseline (Conventional, Steady Burn) LED Implementation of conventional brake lamps Brake lighting: All LED lamps (including CHMSL with three LED lamps) normal illumination level Enhanced rear lighting: All LED lamps (including CHMSL with three LED lamps) normal illumination level (same as brake lighting, no change in brightness)	Baseline	Serves as a comparison benchmark to conventional lighting approach On for a total of 6 s to match other signal durations.

Test Apparatus

As mentioned, this study used the vehicle appliqué mock-up, which was also used in the previous LED Optimization and Attention-Getting studies. This unit, depicted in Figures 5 and 6 (also shown as Figure 21 below for convenience) consisted of a full size appliqué of the rear of a vehicle mounted to a rigid composite metal backing. Observations indicated that at a distance, it was difficult to tell that the appliqué was not a real vehicle. The mock-up included working brake lamp units mounted in appropriate locations on the appliqué (one for the CHMSL and two for the two outboard taillights). Software and hardware were modified from the earlier LED Optimization and Attention-Getting experiments so that all nine test configurations could be presented with the apparatus.

The vehicle in which the participant sat was a late model SUV with an original equipment navigation system installed, as previously described. This vehicle was equipped with data gathering video cameras that recorded the forward view, driver's face, and an over-the-shoulder forward-looking view (Figure 22). From the facial image it was possible to determine if and when the driver looked forward. Thus, it was possible to determine the time interval between presentation of the stimulus (that is, the activation of the rear lighting display at either the brake light level or the emergency level) and the driver's response (if any) to the stimulus.

Figure 21. Vehicle Mock-Up With Working Brake Lamps

Figure 22. Video From the Instrumented Vehicle

Testing Procedure

After obtaining initial informed consent, the study took place in a controlled, static environment using an instrumented vehicle and the vehicle appliqué mock-up to present the rear signaling configurations. Testing took place on the premises at VTTI. Drivers were seated in the instrumented vehicle used to administer the navigation tasks, allowing video of the driver's eye gaze as well as the state of the rear lighting signals to be captured. Following the navigation tasks, that is, the uninformed event detection trials, a subset of the drivers (the 27 who were to perform the ratings) was exposed to all of the lighting configurations across six trials each, as described below:

1. Familiarization Trials. The full set of lighting configurations (nine in all) was presented to drivers. No ratings were collected. Drivers were positioned in the instrumented vehicle at a 100 ft (30.5 m) nominal eye distance from the vehicle appliqué mock-up.

2. Attention-Getting at 100 ft (30.5 m) Looking Forward. Drivers rated the attention-getting capability of each lighting configuration when looking straight ahead as it was presented a second time.

3. Attention-Getting at 100 ft (30.5 m) Looking Off-Angle. Drivers rated the attention-getting capability of each lighting configuration when looking to the right at an angle of 30 deg as it was presented a third time.

4. Glare Rating, Same Lane. The vehicle was moved to an eye distance of 40 ft (12.2 m) from the display. Drivers rated the discomfort glare of each lighting configuration when looking forward as it was presented a fourth time.

5. Glare Rating, Adjacent Lane. The vehicle was repositioned to the adjacent right lane at a longitudinal eye distance of 40 ft (12.2 m) from the display. Drivers rated the discomfort glare of each lighting configuration when looking forward (that is, past the right side of the display) as it was presented a fifth time.

6. Effective Intensity Evaluations. The vehicle was repositioned to an eye distance of 100 ft (30.5 m) directly behind the display, that is, the same position that was used for 1, 2, and 3 above. Drivers were asked to evaluate their impression of the overall effective intensity for each of three lighting configurations (a subset of the nine, to be explained).

Note that participants did not drive the vehicle during any of the tests, but they were asked to reposition the vehicle when necessary between tests (e.g., reposition the vehicle from 100 ft to 40 ft, and move the vehicle to an adjacent lane). During these movements the in-vehicle experimenter guided the participant to park in the correct vehicle position.

Data was collected in direct sunlight with ambient light levels recorded using a Minolta T-10 illuminance meter. It should be noted that this represented a departure from the previous experiments, all of which were run on the shady side of a large storage building. The sun was behind the SUV and therefore shown directly onto the vehicle appliqué display. Because data were gathered in the morning and during midday in April the angle of the sun relative to the horizon was approximately 20 to 30 deg. (note that the SUV faced north and the vehicle appliqué display was directly ahead for all of the same-lane tests).

<u>Effective intensity evaluation</u>

Concerns had been expressed that the attention-getting scale might possibly not be tapping the correct factor in terms of participant ratings and that there was another factor termed “Effective Intensity” that participants should be asked to rate. It was hypothesized that the Effective Intensity factor might provide a better indication of the eye-drawing capability of the display configuration. Therefore, trails to capture effective intensity were developed to test this hypothesis. Effective intensity was defined as “your subjective impression or perception of how bright the lights are, regardless of the pattern arrangement or whether they are flashing or constantly on.”

Effective intensity testing used three lighting configurations, namely configurations 3, 4, and 7 (Table 5). These were repeated after all other tests had been completed so that there would be no forward transfer effects across trials. Participants were first shown the three patterns (in counterbalanced order by participant) and were then asked if the effective intensities were the same or different. If they responded that the effective intensities of the three were the same, there was no further testing. If however they responded that the effective intensities were different, the three lighting configurations were presented again (in the same counterbalanced order as before) and the subject was asked to pick the one with the greatest effective intensity. Then, finally, the process was repeated and the subject was asked to pick the one with the least effective intensity. These latter two tests provided relative rankings for the three configurations.

Recruitment

As previously indicated, 80 individuals were recruited to participate, ranging in age from 20 to 60 years old. Half of the participants were males and half were females. Candidate participants were screened over the phone with a verbal questionnaire to determine whether they were licensed drivers and whether or not they had any health concerns that might exclude them from participating in the study. Individuals who participated in previous rear signaling studies were considered ineligible to participate. Upon arrival at VTTI, eligible participants read and signed an initial informed consent form. They were then given several vision tests including Useful Field of View using the Visual Attention Analyzer.

In regard to useful field of view, complete data was obtained for 79 of the 80 participants. Of the 79, 75 scored in the low-risk category and 4 scored in the slight-to-moderate-risk category. These four were assigned to different lighting conditions in the uninformed event detection task. Only the incandescent TCL condition did not include one of the individuals with slight to moderate risk.

After the uninformed event detection trials, drivers were informed that the true purpose of the experiments was to determine their response to the rear lighting configurations. They then signed an additional informed consent indicating their agreement to allow use of their data and understanding of the real purpose of the study. If the participant was designated to continue with the ratings experiment, the additional informed consent described the ratings portion and also indicated there would be no further surprises.

Data Reduction & Analysis

The principal measures for the testing included the ratings (attention-getting, discomfort glare, and effective intensity) and driver response to the uninformed event detection tests (e.g., glance incidence and latency). For the complete set of lighting configurations, analyses addressed the differences among the various lighting configurations along both dimensions (attention-getting and discomfort glare) using the ratings. In addition, comparisons were drawn for the effective intensity ratings. For the uninformed event detection task, analyses focused on the lighting configuration's eye-drawing capability as measured by the percentage of drivers glancing forward and the associated latency. In this case, the principle method of data extraction was from the stored video of each event. These video images contained frame numbers that allowed the measurement of elapsed time in responses to the lighting configuration, if any. Driver responses to questions about whether or not they noticed the lighting configurations were also analyzed.

Results of the Uninformed Event Detection Portion of the Experiment

The main purpose of this part of the experiment was to determine the eye drawing capability of a subset of the nine rear signalling configurations, namely, configurations 1, 4, 6, 7, and 9 (Table

5). The main method for accomplishing this was data extraction from the video recordings made in the SUV in which the participant sat. The recordings indicated when the rear lighting started, and if and when the participant looked up at the forward (vehicle appliqué) display. Consequently, it became possible to determine the duration between signal initiation and the participant's look up response, if any.

As it turned out, many of the participants did not look up during the first exposure. It will be recalled that the display used a 1 s brake lighting signal followed immediately by a 5 s emergency lighting signal. Measurements were made from the beginning of the *emergency* lighting signal. If the participant did not look up at the display, a value of 6 s was assigned on the assumption that this would be the minimum time in which the participant might have looked up. This would correspond to 5 s plus one additional second after the display had been extinguished. Thus, all responses were scored as the actual response times or 6 s if the participant did not respond.

The data for the first exposure were analyzed first because this situation was totally unanticipated for all participants. The data were analyzed by means of a one-way between subjects ANOVA. Results were significant with $F(4,79) = 3.18$, $p < 0.01$. To determine where significant differences occurred, the results were further analyzed by means of a Duncan's multiple range test. The results are plotted in Figure 23. In the figure, means with a common letter do not differ significantly at the $\alpha = 0.05$ level using the Duncan's test. The plot shows that the baseline braking configuration (Configuration 9) did not cause participants to look up at all, that is, all response times were set at 6 s. Only the outboard simultaneous flash with CHMSL alternately flash (Configuration 7) and the simultaneous flash (Configuration 4) were significantly superior in reducing eye drawing time. Both of these configurations used the increased (emergency) brightness level for the lighting during the last 5 s of the lighting stimulus. Note that the incandescent TCL (Configuration 1) and the simultaneous flash with no increase in brightness (Configuration 6) had some eye-drawing capability, but not to the extent that they were signficantly different from baseline.

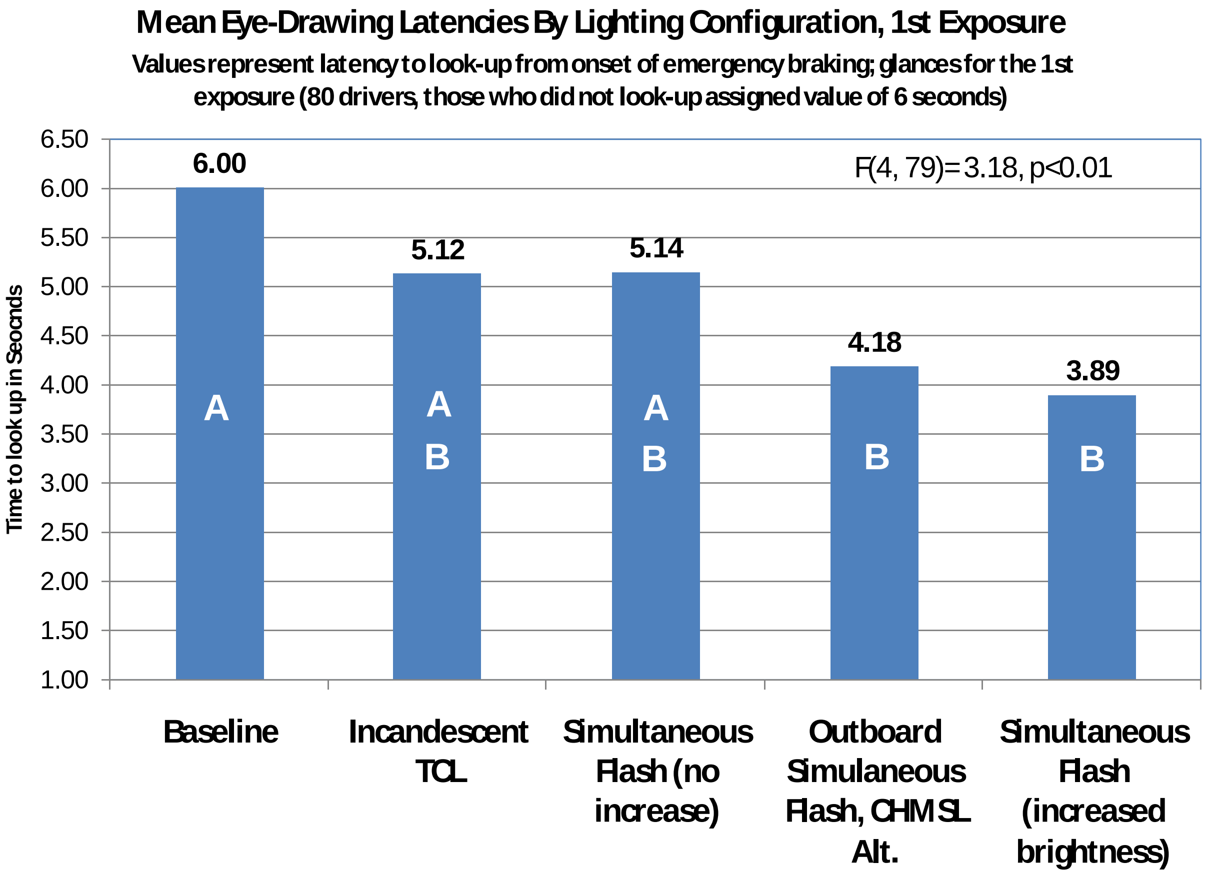

Figure 23. Mean Look-up Response Times on First Exposure to the Lighting Display as a Function of Lighting Configuration

As previously described, there were three exposures to the display lighting as participants worked with the in-car navigation task. The second and third exposures were of course given to each participant in the same way as the first exposure. However, the navigation tasks performed at the time of second and third exposures became progressively more difficult. Once again if a subject did not look up on a given exposure, that exposure was assigned a value of 6 s. If the subject did look up, the actual time duration from emergency lighting start to looking up was used. Data on response times were analyzed using a two way ANOVA with lighting configuration as a between subjects variable with five levels and with exposure as a-within-subjects variable with three levels. Both main effects were significant: lighting configuration, $F(4,79) = 3.65$, $p < 0.009$; exposure, $F(2,239) = 9.96$, $p < 0.0001$. The interaction of these two variables was not significant. Results for the lighting configuration main effect are plotted in Figure 24, and results for the exposure main effect are plotted in Figure 25. Once again results of a Duncan's test are included in each plot.

Figure 24 shows results quite similar to those shown in Figure 23 for the first exposure, in that ordering is similar. However, the values for the best performers in terms of eye drawing capability are now closer to baseline. More will be said about this following investigation of the Exposure main effect. Note once again, however, that baseline did not cause any participant to look up on any exposure, a very important result!

Figure 25 shows that after the first exposure the number of participants looking up decreased, or in other words, response times more closely approached the assigned 6 s value. These results suggest that as the visual/cognitive/manual load of the navigation task increased, participants narrowed their concentration and tended to neglect other potentially strong visual cues, such as the vehicle appliqué display activations. Note that the first exposure involved having the experimenter explain the navigation system while the participant looked at it. The second exposure involved having the participant scroll through a menu, and the third involved entering a city name using an alpha-numeric keypad and finger joystick. The results are believed to represent an example of perceptual narrowing caused by increased task loading. Of course, there was also the countervailing factor of repeat exposure in which participants might have neglected the vehicle appliqué lighting purposely. To determine how these factors interacted, participants were interviewed in regard to what they saw or didn't see. These additional results are presented later in this section.

Other exploratory results were also developed for the data. Figure 26 shows the percentage of participants who looked up as a function of exposure. This plot shows very clearly that look-up percentage dropped off very rapidly with exposure. The percentage results were subjected to a chi-square analysis and were found to be significant as a function of exposure $\chi^2(2,240) = 21.7$, $p < 0.0001$. Post hoc chi-squared paired comparisons between each pair of percentages were also significant ($\alpha = 0.05$) and are designated by different letters associated with the first, second, and third exposures.

Less formal results were also developed for the percentage data. Figure 27 shows the percentage of participants who looked up as a function of exposure and lighting configuration. Statistical tests were not performed on these data. The plots show the same decreasing trend for each of the four non-baseline data sets. Baseline had 0 percent look up in all three exposure cases. An important finding is that 56 percent of drivers looked up on first exposure when the vehicle appliqué display simultaneously flashed all lights at the emergency lighting level (lighting Configuration 4). This result suggests that a relatively high percentage of drivers could be alerted to a problem ahead if they are looking away and are performing a task that is not too heavily loading. Equally important is the finding that while flashing alone is somewhat helpful, flashing with increased (emergency) lighting level is far more effective. Only 19 percent of participants looked up for flashing at the normal brake lighting level, whereas the percentage for flashing with emergency level lighting is nearly three times as high. *This result is quite compelling in regard to justification for use of the emergency lighting level.*

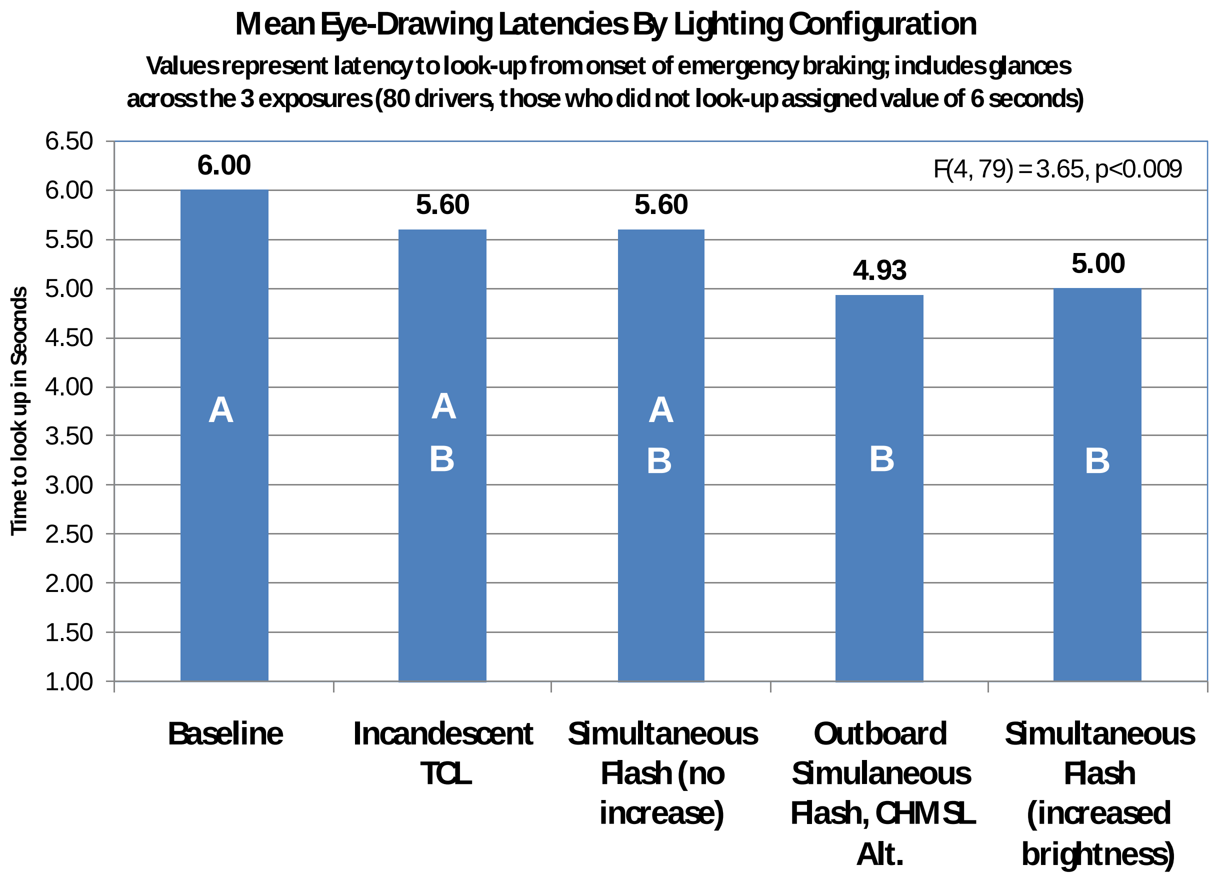

Figure 24. Mean Look-up Response Times Averaged Across the Three Exposures to the Lighting Display as a Function of Lighting Configuration

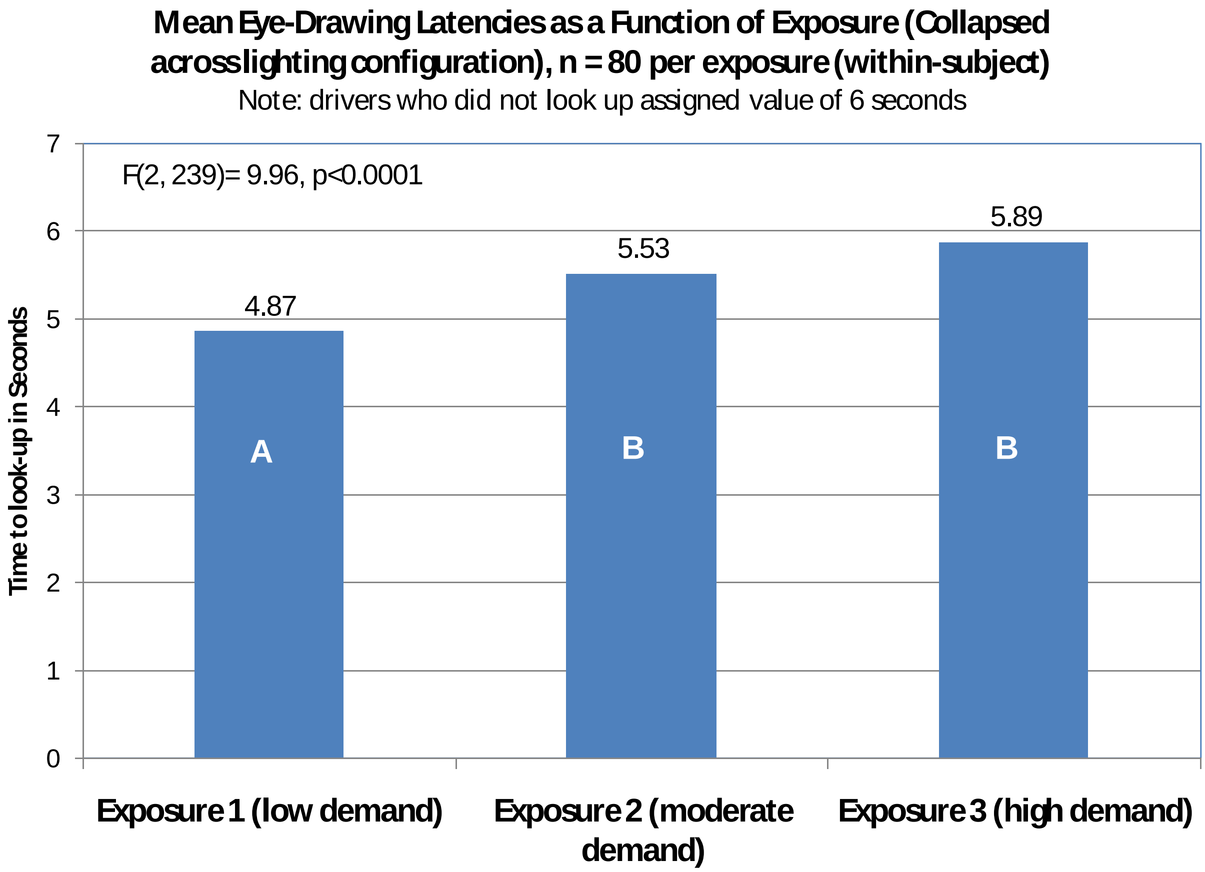

Figure 25. Mean Look-up Response Times Averaged Across the Five Lighting Configurations, as a Function of Exposure

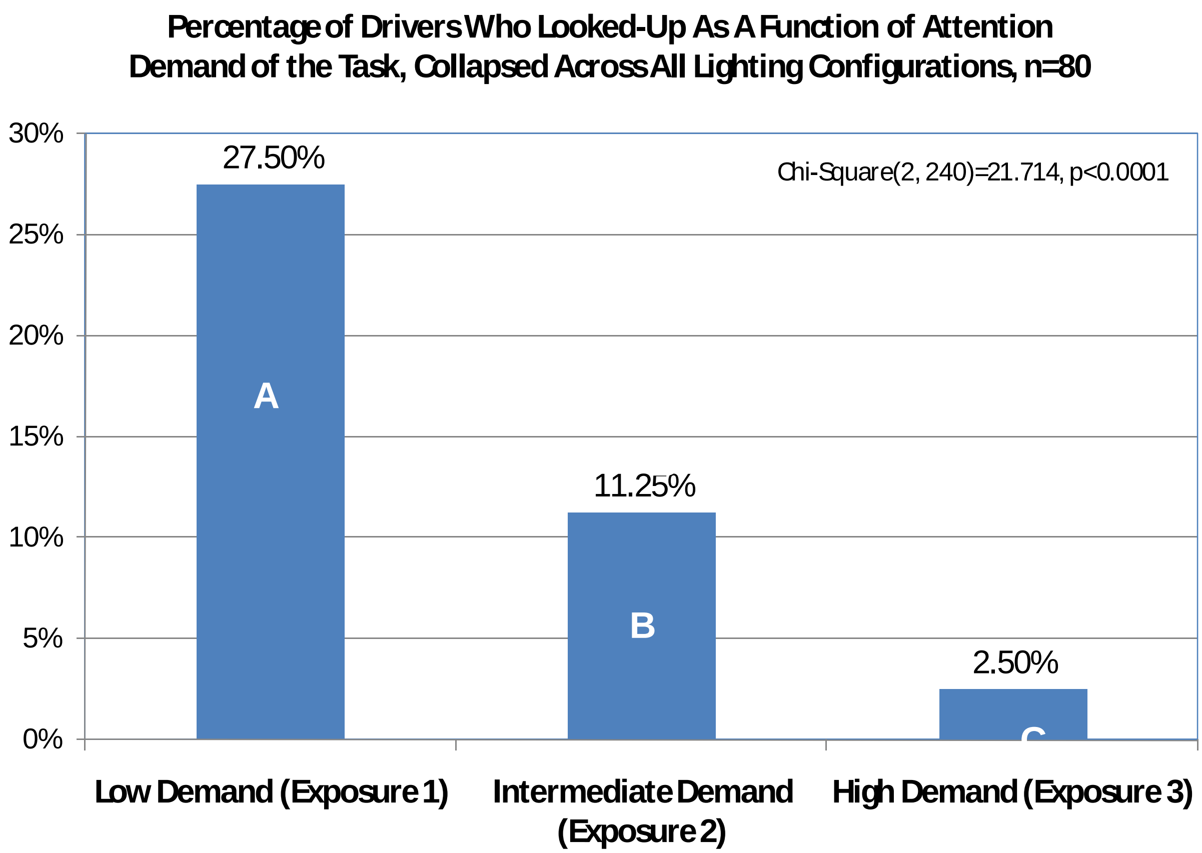

Figure 26. Percentage of Participants Who Looked up at the Lighting Display as a Function of Exposure

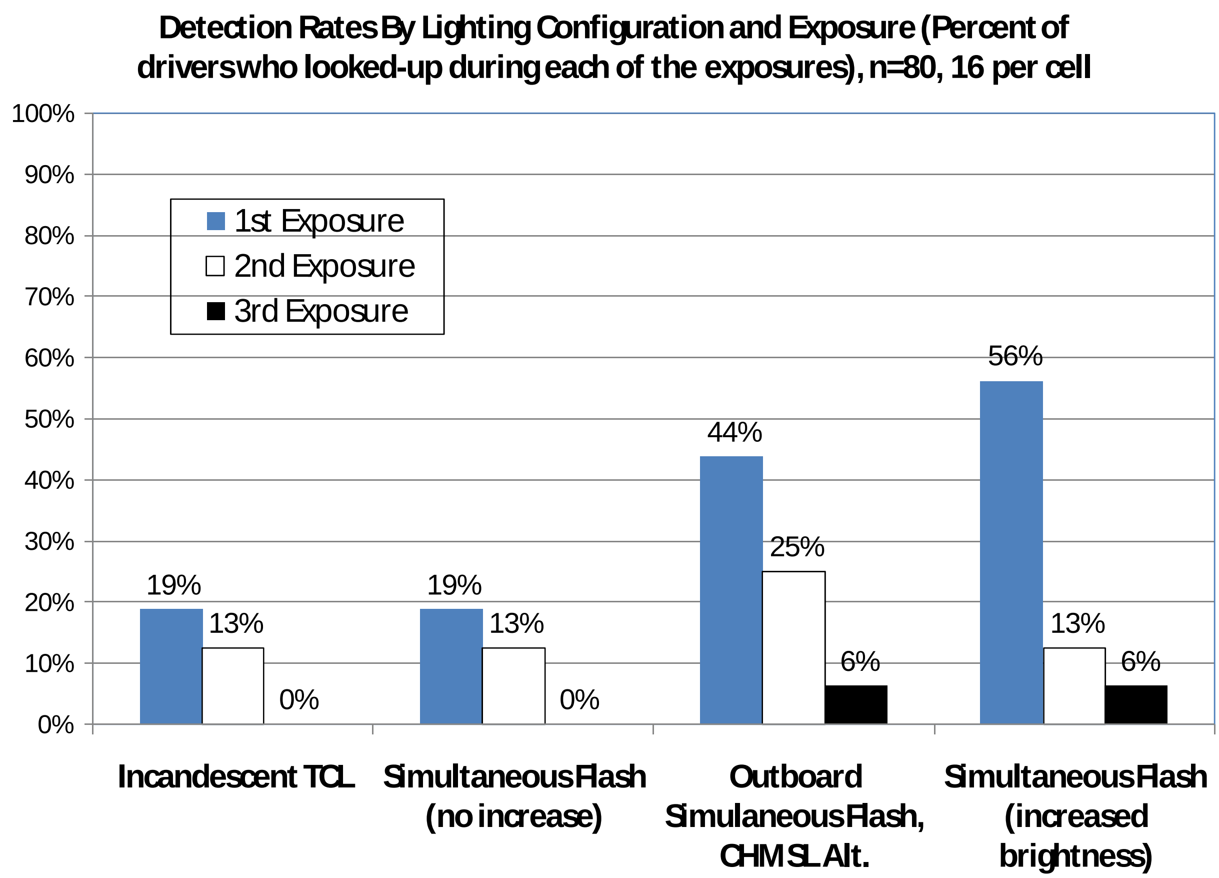

Figure 27. Percentage of Participants Who Looked up as a Function of Lighting Configuration and Exposure. Note That for Baseline, None of the Participants Looked up on Any Exposure. (Results Are for Explanatory Purposes and May Not Be Statistically Significant Except as Previously Indicated.)

In regard to interview questions about what the participants saw (Appendix C), it will be recalled that three consecutive questions were asked of the participants. Only those who answered affirmatively on the first question received the second question, and only those who answered affirmatively on the second question received the third question.

For the question "Did you notice anything unusual outside at any time while we were working with this navigation system?" 26 subjects (33%) answered affirmatively. All of them identified the lighting of the lead vehicle as the unusual event. The data for this question was analyzed further as a function of lighting configuration. Specifically, the number of "affirmatives" as a function of the five lighting configurations was analyzed using a chi-square test and found to be significant, $\chi^2(4) = 21.31$, $p < 0.001$. Post hoc chi-square tests produced results as shown in Figure 28.

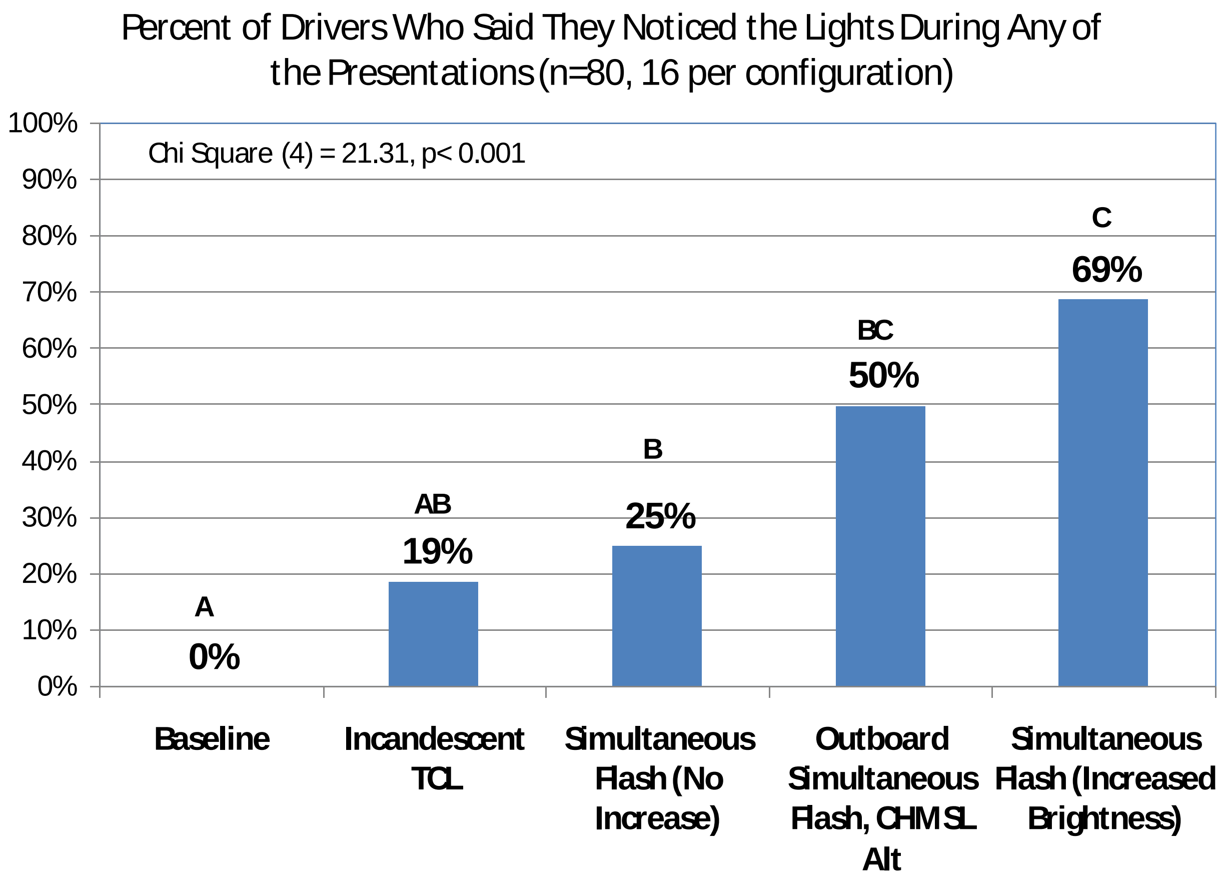

Figure 28. Percentages of Participants Who Said They Noticed the Lights During the Navigation Tasks as a Function of Configuration

These results are quite informative by themselves. In addition a careful check was made of how well video-recorded "look ups" corresponded with these interview results. Figure 29 shows the results for the video-recorded look ups. Again a chi-square test was significant $\chi^2(4) = 24.25$, $p < 0.001$. Post hoc chi-square tests are as shown in the figure. Comparison of Figures 28 and 29 indicates that there is little difference. Additional checks showed that subjects who looked up (by configuration) were the ones who said they noticed the rear lighting.

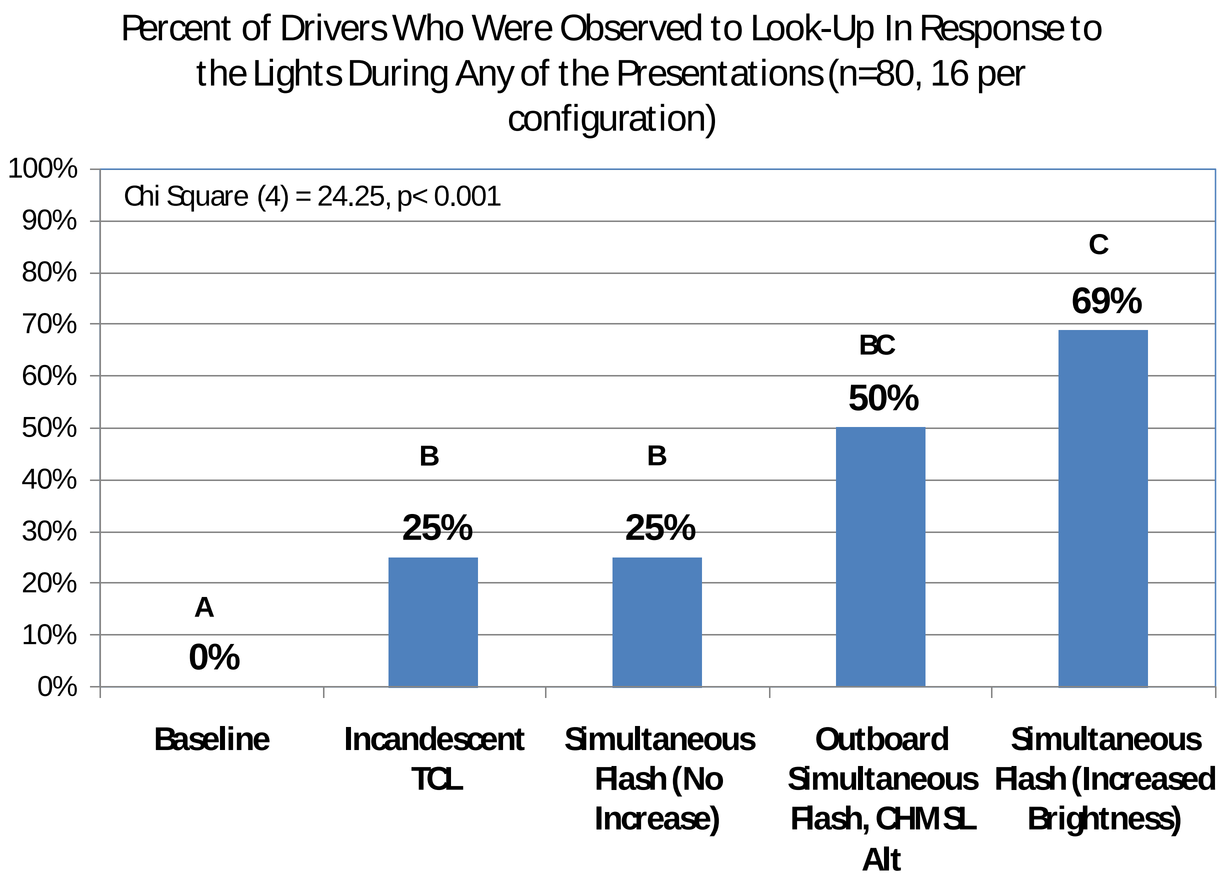

Figure 29. Percentages of Participants Who Actually Did Look up (Derived From Video Recordings)

Results of the post hoc tests indicate that all three LED signal configurations led to improved eye drawing capability over the conventional (baseline) braking signal, and that the simultaneous flashing with increased brightness demonstrated superior performance relative to the other configurations with the exception of the outboard simultaneously flashing, CHMSL alternately flashing. Of particular interest is that while simultaneous flashing of brake lamps without an increase in brightness led to significant improvement over baseline, pairing the flashing with increased brightness significantly enhanced the eye drawing capability, nearly tripling it compared with flashing alone. A significant 69 percent of participants noticed the lighting on at least one occasion when simultaneous flashing and increased brightness were combined. This compares to 0 percent for the baseline configuration.

The remaining two questions were analyzed descriptively only. The second question was, “Did it happen more than once?” Thirteen of the 26 drivers (50%) said yes. Of these 13, responses to the third question, “How often did it happen?” are shown in Figure 30. Responses for the 13 participants are shown as percentages. Results indicate that a variety of responses occurred, as expected.

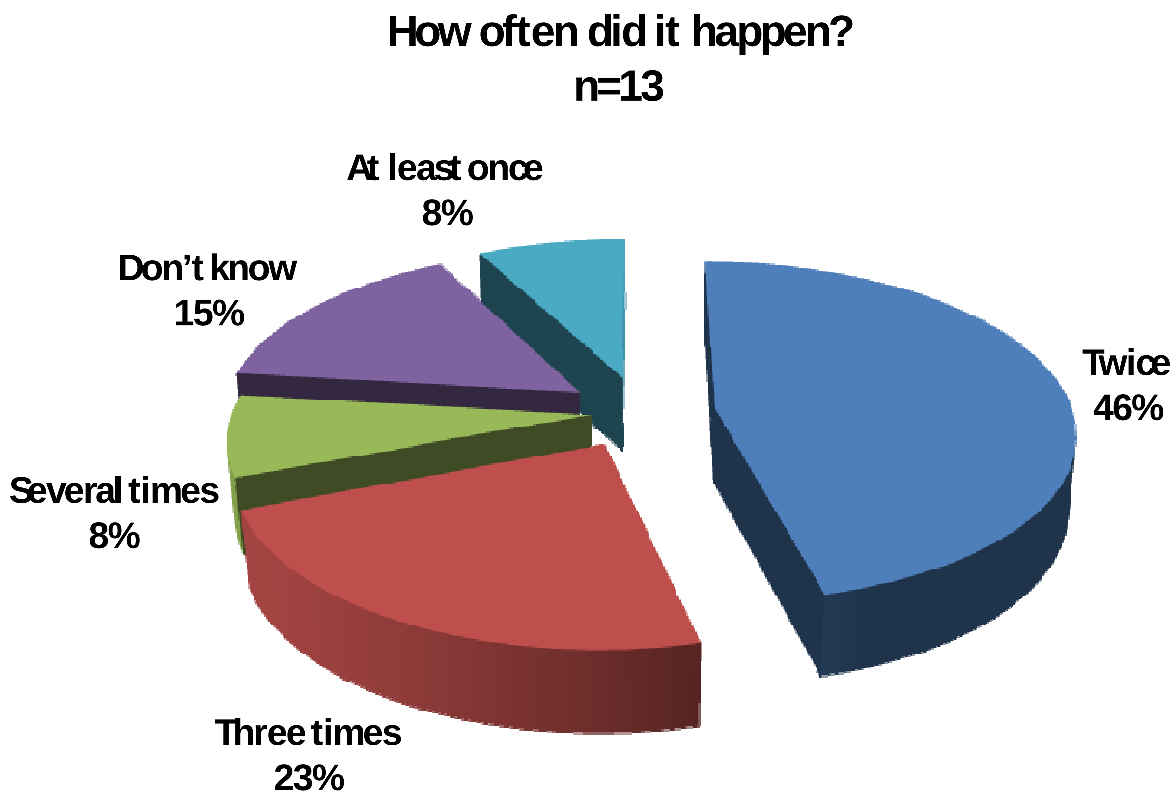

Figure 30. Pie Chart of Responses to the Third Question, "How Many Times Did the Lights Appear?"

Finally, in regard to the uninformed event detection portion of the experiment, illuminance level was examined. The purpose was to determine if light level when the data were gathered might have influenced or biased the data for the five uninformed event display conditions. The meter measuring illuminance was placed on the ground and aimed straight upward just prior to beginning the navigation task instructions. The same spot on the ground was used for every run. A one-way ANOVA was run with lighting configuration as the independent variable and illuminance level as the dependent variable. There were 16 data for each setting of the independent variable. The result of the ANOVA was that configuration was not signficant, and in fact was far from it, $F(4,78) = 0.99$, $p = 0.416$. This result indicates that illuminance level did not change in a systematic way across the testing of the five configurations. Descriptive statistics were as follows: grand mean, 79,884 lx; standard deviation, 19773 lx; range minima and maxima across all subjects, 35,000 to 116,600 lx.

Results of the Ratings Portion of the Experiment

This experiment, as previously described, was performed after the Unanticipated Event Detection Experiment by 27 of the participants. Weather conditions were the same for this follow-on experiment, in which the participants provided ratings while looking at or past the vehicle appliqué display. They first experienced all 9 configurations (Table 5) in counterbalanced order in a familiarization trial at an eye distance of 100 ft (30.5 m). They then were shown each configuration activation again and rated it for attention-getting using the scale shown in Figure 8. Immediately thereafter they were again shown the configurations as they looked to the right 30 deg (fixating on a small target attached to a stand 100 ft (30.5 m) away and approximately 3 ft (0.91 m) high, and again evaluated the attention-getting using the same scale.

The ratings were subjected to a two-way within-subjects ANOVA and demonstrated significance in both main effects and their interaction: Configuration, $F(8,485) = 74.35$, $p < 0.0001$; Direction, $F(1,485) = 166.85$, $p < 0.0001$; and Configuration by Direction, $F(8,485) = 4.40$, $p < 0.0001$. Results are plotted in Figure 31. As expected, direct looks at the vehicle appliqué display resulted in higher ratings than when looking 30 deg to the right. However, the significant interactive effect shows quite clearly that there are differential effects within the on- and off-axis ratings. Note that the better configurations to the right in the graph have proportionally smaller changes when going to off-axis ratings, suggesting better ability to capture attention for drivers who are looking away. Also, while the incandescent TCL yielded faily high attention-getting rating when looking forward, ratings were observed to drop sharply when viewed off-angle, suggesting that this is not as effective as other higher-rated signals.

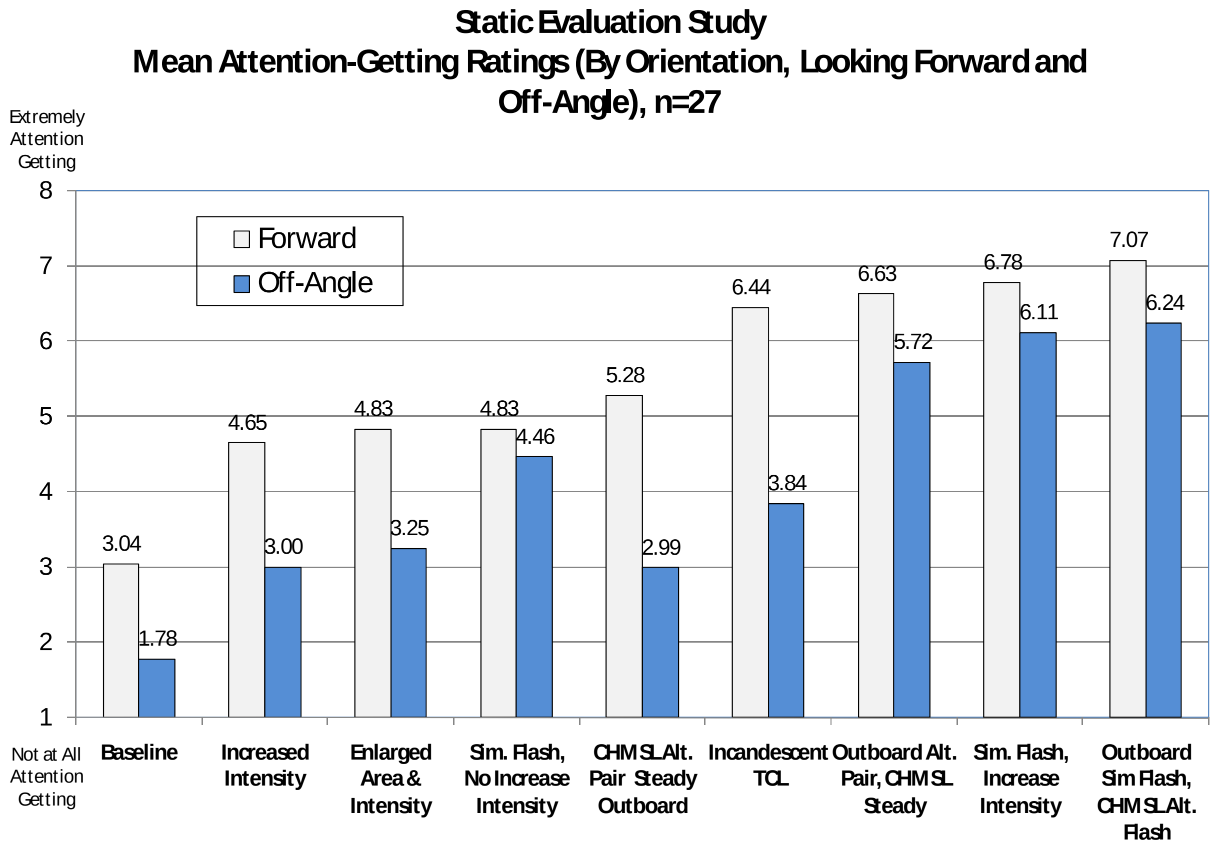

Figure 31. Attention-Getting Ratings as a Function of Lighting Configuration and Eye Fixation Direction.

The main effect of configuration is shown in Figure 32. Post hoc Duncan's multiple range test results are also shown. These results suggest that both flashing and brightness are effective in increasing the attention-getting ratings. Note in particular that flashing alone (center bar in the graph) causes a reduction in rating values that is more than 1.5 rating points lower that the average of the top three configurations, all of which make use of the higher (emergency) lighting level. This result is similar to those shown in Figures 23, 24, and 27 for the uninformed event detection portion of the experiment in that increased brightness shortens detection time and improves the percentage of participants who looked up at the lighting display.

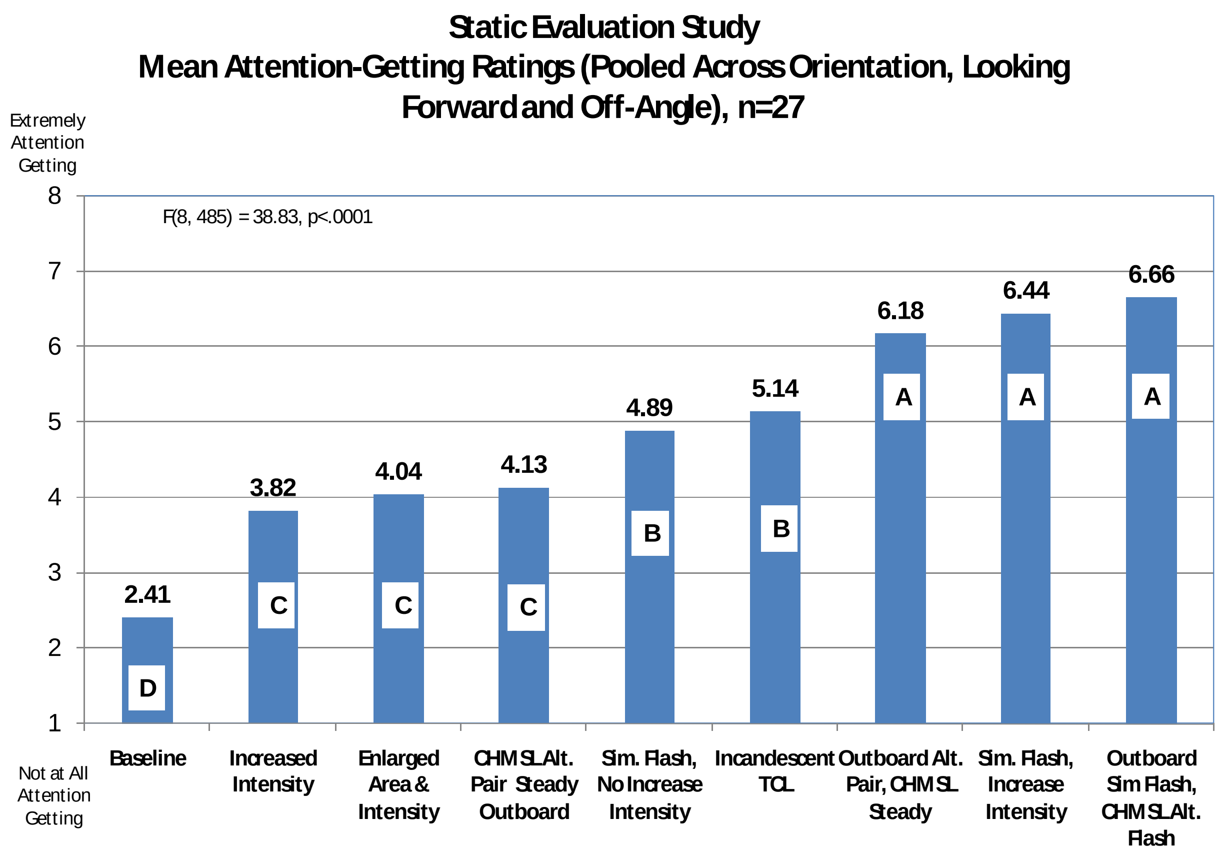

Figure 32. Main Effect of Lighting Configuration on Attention-Getting Ratings

Glare ratings were analyzed using a similar methodology. Ratings were performed at an eye distance of 40 ft (12.2 m) in the same lane as the vehicle appliqué display and in the adjacent lane to the right at the same longitudinal distance. In the latter case, participants were instructed to look forward (past the display) and not directly at the display. Both the main effects of lighting configuration and lane position were significant, as well as the interaction of these two independent variables: Configuration, $F(8,485) = 38.83$, $p < 0.0001$; Position, $F(1,485) = 400.5$, $p < 0.0001$; and, Configuration by Position, $F(8,485) = 6.99$, $p < 0.0001$. Figure 33 shows the results as a function of the two independent variables. The results are presented in the same order in regard to configuration as the attention-getting ratings. The results show clearly that the glare ratings for the better attention-getting ratings fall in the middle range for glare. The incandescent TCL stands out as having higher glare, a result that is not too surprising considering its sweeping coverage as compared with the LED lamps (all other configurations). It is further to be noted that the adjacent lane ratings are much lower than the same lane ratings. In all cases except the TCL the beam coverage was quite narrow (approximately 7 deg), so it is not surprising that participants perceived the glare to be much lower. Of course, they also were instructed to look forward and not into the display, which no doubt had an effect.

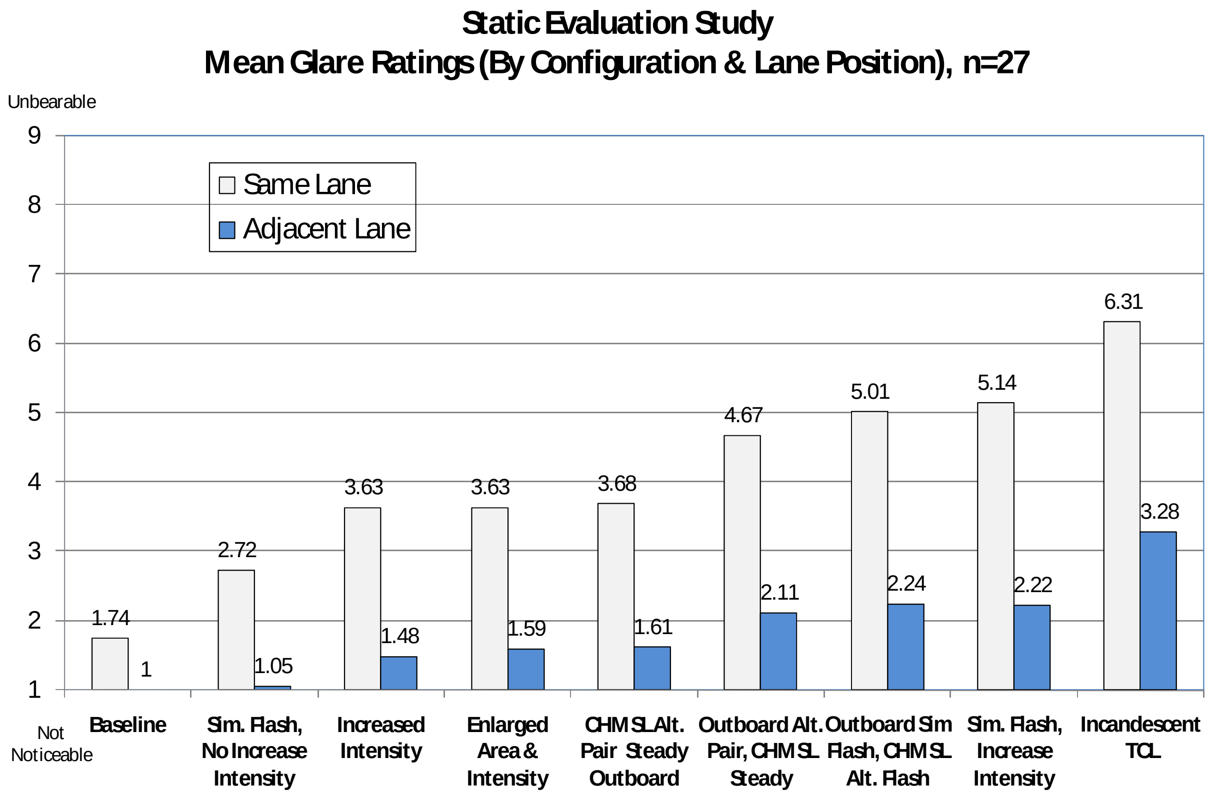

Figure 33. Effects of Lighting Configuration and Lane Position on Rated Discomfort Glare

The main effect of configuration is shown in Figure 34 along with post hoc results of the Duncan's multiple range test. The graph has been re-ordered from least to greatest main effect glare. The graph shows that the incandescent TCL creates greater discomfort glare than do the better LED configurations. Nevertheless, there is clearly a relationship between glare and attention-getting, in which glare can be expected to increase somewhat with attention-getting capability. This result has been seen in previous work with rear lighting displays. However, the narrow beam width of the LED displays limits the glare for drivers in adjacent lanes, a desirable characteristic. (It can generally be assumed that drivers in adjacent lanes are not the ones who are likely to strike the vehicle on which the emergency lighting has been installed.)

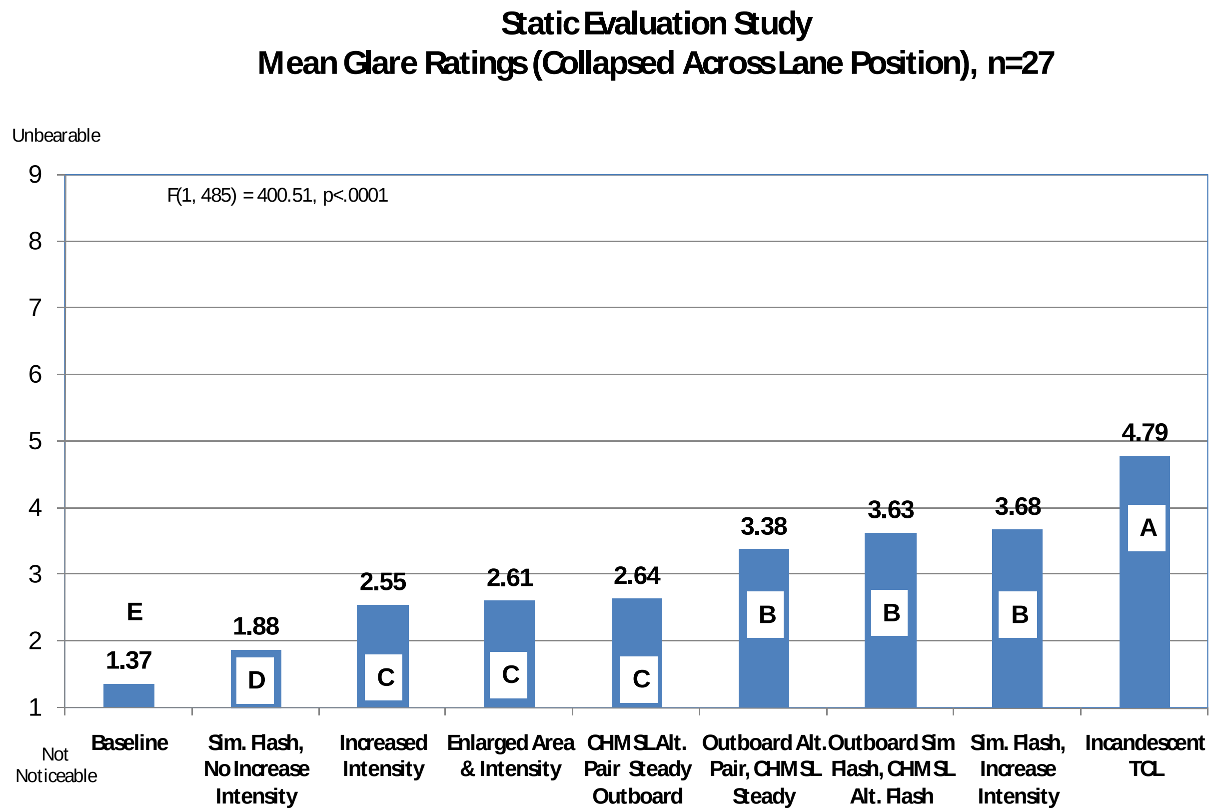

Figure 34. Main Effect of Lighting Configuration on Discomfort Glare Ratings (in Ascending Order)

Because of the importance of same-lane glare, the results shown in Figure 33 in regard to same lane were re-plotted along with results of a corresponding Duncan's multiple range test. These results use the same order of presentation as Figure 33, and are shown in Figure 35. The results show that the best LED configurations in terms of attention-getting ratings and uninformed event detection cluster around a discomfort-glare rating value of 5. This value corresponds to "Just Acceptable, I might want to look away in less than a minute," which would probably be acceptable to drivers. Note that in the great majority of circumstances the lighting would be activated for not more than 6 s.

It will be recalled that the final task of the 27 participants who performed the ratings was to assess the effective intensity of three configurations. This test was performed after all other tests so that there would be no transfer effects to the previous tests. The three lighting configurations

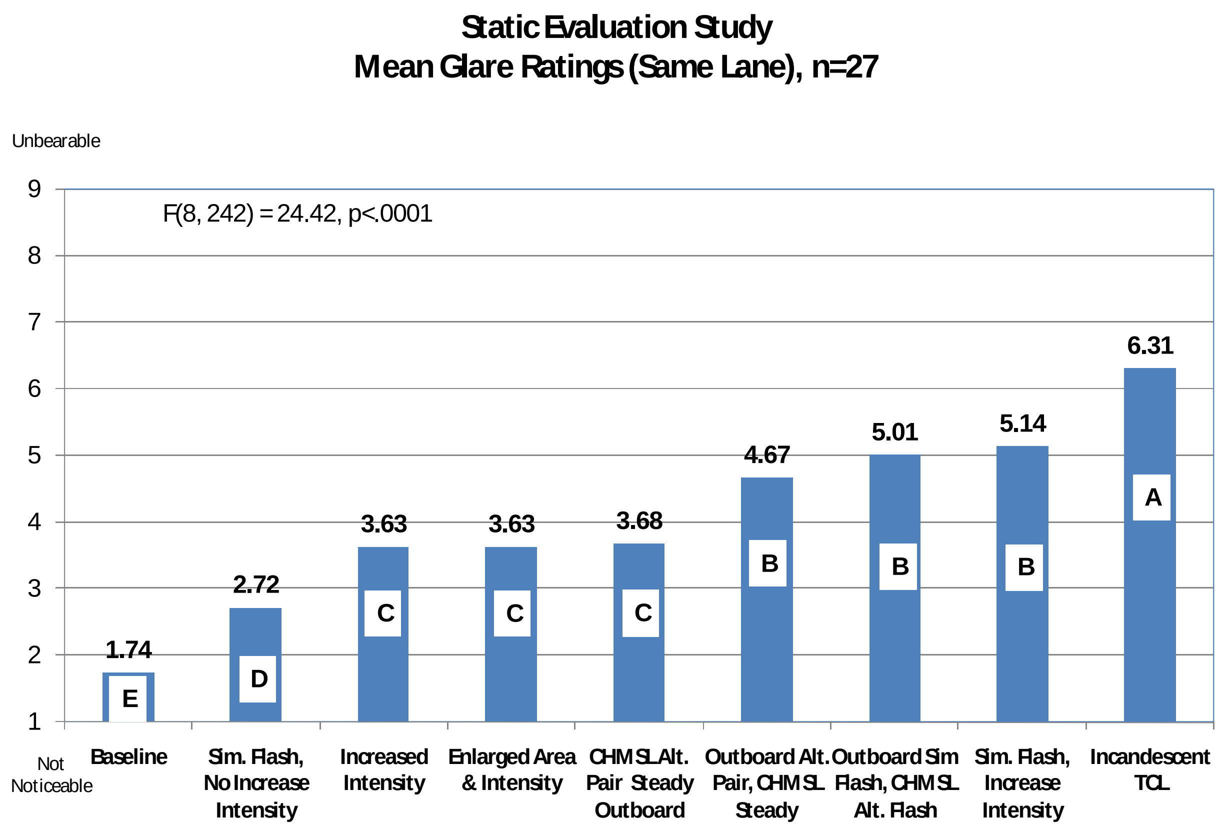

Figure 35. On-Axis Glare Ratings With Post Hoc Duncan's Test Results

used in this test were Configuration 3 (increased steady intensity) for the emergency portion, Configuration 4 (simulateous flashing of all lamps at increased intensity) for the emergencey portion, and Configuration 7 (outboard simultaneous flash, CHMSL alternate flash at increased intensity) for the emergency portion. Note that all three of these configurations used increased intensity during the emergency portion. The only differences were in the presence/absence of flashing and in the pattern of the flashing.

Initially, a chi-square test was performed on the data to determine if the number of participants who said there was a difference in the effective intensity differed significantly from the number who said there was no difference. As it turned out, 17 participants said there was a difference. Results of the test were not significant, $\chi^2(1) = 1.81$, $p = 0.18$. Even so, the relative rankings of the 17 were analyzed by means of another chi-square test. In particular, the first place rankings were analyzed. Results again indicated a lack of significance, $\chi^2(2) = 0.82$, $p = 0.66$. Figure 36 shows the relative proportions of first place votes (noting once again that the results are not significant) for information purposes. These results indicate that effective intensity as defined for the participants is not as sensitive a measure as either the previous ratings or the previous eye-drawing tests. Consequently, the previous measures should be retained, and it appears there is little, if anything, to be gained by introducing this new measure.

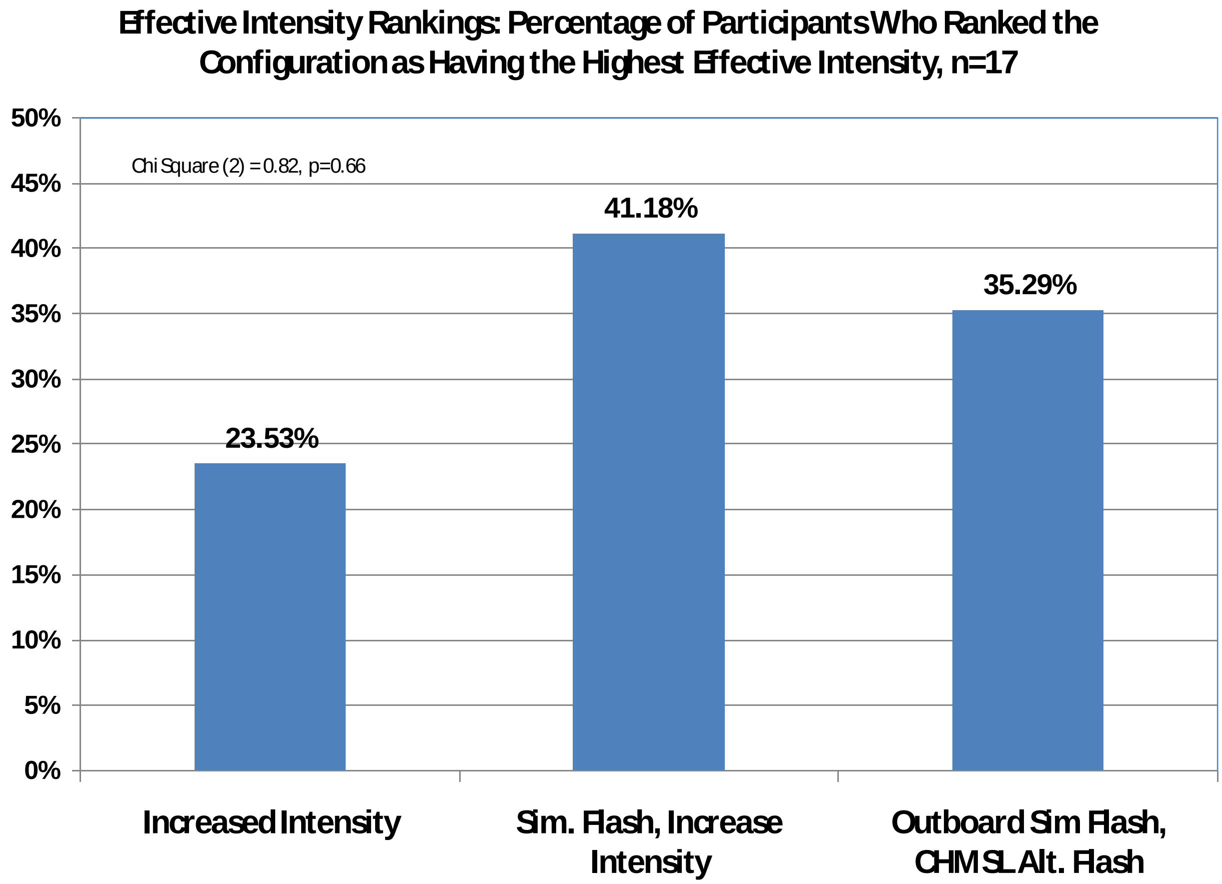

Figure 36. Percentage of First Place Ranks of Effective Intensity by the 17 Participants Who Said There Were Differences. Note That Differences Are Not Significant

Experiment Summary

The results of the experiment are quite illuminating and point the way to on-road tests. Here in outline form are the main findings:

<u>Uninformed Event Detection Experiment</u>

1. During the first exposure, participants looked up to the rear lighting display 56 percent of the time while glancing to the navigation display under light load for Configuration 4 (simultaneous flash, increased brightness) that simultaneously flashed all rear lighting at the (high) emergency light output level. In this case, participants had not been previously

exposed to the rear lighting and they were uninformed about it. These are the cleanest data in which subjects were totally uninformed and not previously exposed.

2. Participants looked up to the rear lighting display 19 percent of the time while glancing to the navigation display under light load for Configuration 6 (simultaneous flash, no increased brightness) that simultaneously flashed all rear lights at the normal brake lighting level. Thus, simply flashing at the current lighting level provides a small improvement, but not nearly as much as also increasing the brightness.

3. Participants did not look up any to the rear lighting display while glancing to the navigation display under light load for Configuration 9 (conventional brightness, steady burn) that was the baseline configuration in which the brake lighting was simply extended. This result suggests that there is no eye-drawing effect with the LED version of the baseline configuration reflecting the current level of rear lighting when the lead vehicle is in morning sunlight. Thus, current lighting appears to be totally ineffective in this case, according to the results of the current study.

4. Both look-up (eye drawing) data and interview data support the hypothesis that simultaneous flashing of all rear lighting, combined with increased brightness would be effective in redirecting the driver's eyes to the lead vehicle when the driver is looking away with tasks that involve visual load. Further indications are that as cognitive load increases, some perceptual narrowing occurs. This narrowing reduces, but does not eliminate, the effectiveness of this form of rear lighting.

5. For the three exposures to the rear lighting configurations, the eye-drawing data and the participants who said they detected the lighting were identical in terms of numbers of occurrences. In total, 69 percent of subjects looked up on one or more exposures to the Configuration 4 (simultaneou flash, increased brightness), having simultaneous flashing and increased brightness. In comparison, 0 percent looked up on one or more exposures for the baseline, Configuration 9, as previously stated.

6. The results generally support Configuration 4 (simultaneous flashing and increased brightness) as most effective in drawing the participants eyes back to the forward view. They also support the fact that current rear lighting is totally ineffective in drawing the participants eyes back to the forward view. These results are for the case in which bright daylight floods the lead vehicle and the subject is involved in an in-car task requiring visual and cognitive load, a task that could be considered typical of more complex in-car tasks.

7. The incandescent TCL (Configuration 1) had lower eye drawing capability than Configuration 4, and was also rated to have lower attention-gettingness when looking off-angle This device proved most effective in earlier studies. Consequently, it can be

assumed that Configuration 4 is the most effective configuration evolved thus far in terms of eye drawing capability.

8. The development of an alternative measure of effectiveness “effective intensity” did not prove to be successful. Therefore, the attention-getting ratings and the eye drawing capability should be retained as the most effective measures.

Ratings Experiment

In terms of attention-getting, whether looking straight ahead at a distance of 100 ft (30.5 m) or looking to the right at an angle of 30 deg., subjects rated Configurations 4, 8, and 7 as the most attention-getting (these configurations correspond to simultaneous flash with increased brightness; outboard alternating pair and CHMSL steady; and outboard simultaneous flash with CHMSL alternating). While Configuration 4 flashed all lights simultaneously, Configuration 8 flashed the outboard lamps alternately with a steady CHMSL, and Configuration 7 flashed the outboard lamps simultaneously with the CHMSL flashing alternately. All three configurations used increased brightness. Clearly, flashing and increased brightness play a major role in attaining high ratings by the research participants.

The incandescent TCL configuration (Configuration 1) was rated 1.28 rating points lower on average, as compared with average of the top three rated configurations (Configurations 4, 8, and 7) in terms of attention-getting. This result suggests that the newer lighting configurations are somewhat better in terms of attention-getting.

The use of simultaneous flashing of all rear lighting, but with no increase in brightness (Configuration 6) was rated 1.53 rating points lower on average, as compared with the top-three rated configurations (Configurations 4, 8, and 7). This suggests that flashing alone is not nearly as effective as flashing combined with increased brightness.

The baseline configuration (Configuration 9) that used neither flashing nor increased brightness was rated 4.01 rating points lower on average, as compared with the top-three rated configurations (Configurations 4, 8, and 7). This is a remarkably large difference and corresponds quite well with the results of the Uniformed Event Detection Experiment that demonstrated *no* eye drawing capability for Configuration 9. This rating result similarly shows that current lighting configurations are relatively ineffective at drawing attention in daylight.

In terms of discomfort glare, the incandescent TCL had the highest ratings (greatest discomfort glare) whether rating from directly behind or rating in the adjacent lane looking forward. This result is not too surprising, considering that the TCL sweeps horizontally in such a way that it would cover adjacent lanes at a distance of 40 ft (12.2 m). The LEDs used in all the other configurations had horizontal beamwidths of 7 deg, (3.5 deg to each side of the longitudinal axis) and therefore would be heavily attenuated when viewed from an adjacent lane.

The top ranked configurations in terms of attention-getting were also those that ranked relatively high in terms of discomfort glare. More specifically, Configurations 4, 8, and 7 ranked just under a value of 5 in terms of discomfort glare on-axis. This value corresponds to "Just acceptable…I might want to look away in less than a minute." Clearly, since the emergency lighting would likely be used for 6 s or less, these top configurations would probably not cause unacceptable discomfort glare.

In terms of the adjacent lane discomfort glare ratings at a longitudinal distance of 40 ft (12.2 m), the top three configurations were all ranked in the range averaging 2.2. These values are sufficiently low that discomfort glare would not be a problem for drivers in adjacent lanes.

General Conclusions

It is quite clear from the results of the ratings experiment that there are three configurations that are quite good in terms of attention-getting ratings. These configurations are Configuration 4 (simultaneous flashing of all lamps with increased brightness), Configuration 8 (outboard lamps alternately flashing, CHMSL steady, all at increased brightness), and Configuration 7 (outboard lamps flash simultaneously, CHMSL alternately flashing, all with increased brightness). However, Configuration 4 has the edge in eye drawing capability. Thus Configuration 4 is the recommended configuration. It is the most viable candidate for on road testing. All three of the top ranked configurations also have acceptable discomfort glare when used in bright light.

In terms of flashing alone (*without* increased brightness) there is very modest improvement in eye drawing and attention-getting; however, this configuration is far less effective than flashing *with* increased brightness insofar as the testing performed in the current study is concerned. Also, steady ordinary braking levels appear to be totally ineffective in drawing the driver's eyes to the forward view for the conditions tested in the current study. It appears therefore that there is much to be gained by flashing and increased brightness. Fortunately, adequate light output levels can be achieved with present day LED technology.

Chapter 4. Initial On-Road Evaluation of Candidate Rear Lighting Configurations in Regard to Response Behavior and Eye-Drawing Capability

Study Purposes and Objectives

This on-road study represents the first controlled introduction of the candidate rear lighting signals to the naïve driving public. The purposes of this study were to determine how drivers would respond to the top candidate rear lighting condition (as determined by previous static tests) and to determine to the extent possible whether drivers would redirect their eyes forward when they were looking away. An additional purpose was to compare this candidate with baseline (that is, ordinary rear lighting) as well as one of the promising concepts being recommended by one of the automobile manufacturers. In traffic, the driver is usually looking forward. In an application, there will be many incidents in which the rear lighting will be triggered *while* the driver is looking forward. This experiment was set up to determine whether drivers, on encountering the new lighting, would react differently than when encountering a typical baseline braking signal. In addition, static tests have shown substantially better eye drawing capability for the top alternative candidate, and it was desired to test this capability on road to the extent possible. This would mean that the on-road experiment would require "catching" at least some drivers looking away and then activating the rear lighting. Thus, part of the planned experiment was directed toward detecting when following drivers were looking away.

In this on-road experiment, there was no actual braking associated with the (lead) vehicle on which the lighting was installed; consequently, risks were minimized. The concept was to activate the rear lighting to determine what the following driver's reaction might be. Some reactions were expected to demonstrate following driver braking or slowing somewhat, while other reactions were expected to represent caution, perhaps by stepping on the brake, but not depressing it to any appreciable extent. Still others might simply lift their feet from the accelerators (which could not be determined in the experiment). To capture reactions, to the extent possible, a confederate vehicle was used. It followed the lead (equipped) vehicle and the following vehicle with the naïve driver and recorded video that showed when the lead vehicle initiated lighting and what the following driver's reaction was (again, to the extent possible).

In regard to rear lighting and signaling, there are other issues of major importance, including criteria and thresholds for triggering the rear lighting, and effects of other approaches such as sound alerts. However, this first road test was directed toward following driver reaction to the lighting and possibly, the eye-drawing capability of the lighting. Data was captured on public roadways with low to moderate traffic densities using a research vehicle equipped with the candidate rear lighting configurations and instrumentation (rear facing video) to capture the reaction of following drivers. Data collected using this on-road approach served as a further method of evaluating candidate rear signaling configurations by helping to determine any potential unintended consequences of the lighting and possibly by providing estimates of eye-drawing capability.

This first on-road study was actually directed toward answering a larger group of questions, the main ones of which have already been stated above. However, a full list of questions, corresponding hypotheses, and analysis metrics was developed and is contained in Table 6. It was recognized that not all of these questions could be fully answered. Nevertheless, the on-road study was designed to shed light on the questions, and to determine at least initially whether or not the hypotheses were likely to be correct.

Table 6. Roadway Evaluation Study Key Questions, Hypotheses, and Analyses

Question	Hypothesis	Cases, Metrics, and Analysis
Are the experimental braking signals providing a benefit to following drivers who are looking away from the forward roadway at the onset of lead vehicle "braking"? To what extent do they capture and redirect the driver's gaze forward?	Previous work suggests that the experimental signals have an eye-drawing effect; a tendency to draw the driver's eyes forward compared to the conventional brake lights. It is believed this is due to the inherent properties of the experimental signals (flashing and brightness). This effect is expected to generalize to like situations in the real world.	Restrict cases to drivers who were observed to be looking away at the onset of the braking signal. **Latency for driver to look forward**, back to the roadway, following signal activation. Compare this value to baseline condition.
Are the experimental braking signals providing a benefit for following drivers who are looking forward at the onset of lead vehicle "braking"? (Eye-drawing component drops out, but do the signals provide additional benefit? To what extent do they evoke a braking response?)	Experimental signals are expected to serve as a salient and meaningful cue to drivers that the lead vehicle is "braking" (even under the tested conditions where the lead vehicle is not decelerating), and therefore drivers are expected to brake in response to the signals (at least initially). If this effect is demonstrated, it suggests that the signal is a powerful cue, evoking a brake response – independent of lead vehicle deceleration. Note: If the frequency of braking is comparable to baseline, this still is a positive piece of evidence – suggests that the experimental signals are not making the situation worse (drivers are responding by braking at the same rates as conventional signal) – drivers understand the meaning to be a braking signal.	Restrict cases to drivers who were observed to be looking forward at the onset of the braking signal OR simply use all cases, excluding those where we know the driver was looking off-road at the onset of the signal (landmark triggers). The assumption is that most drivers will likely be looking forward. **Incidence of subject vehicle braking events -** Compare percentages of braking events under experimental lighting to conventional braking signal. Examine brake activation rates over the entire 5 second exposure period, and up to 1 second after the signal extinguishes. **Brake reaction times** -Compare brake reaction times of the subject vehicle under experimental signals to

		conventional brake signal. Expect the experimental signals will yield faster brake response times, or at least equivalent response times to conventional signals (no delay in braking associated with experimental signals is also a positive result). **Brake duration -** Expected to be longer duration for experimental signals relative to conventional lights.
Are the experimental braking signals producing unintended or undesirable behavioral responses?	Signals are novel cues and may lead to unexpected behaviors. Signals are expected to be interpreted as a braking cue, and therefore should not produce negative behaviors (types of incidence of negative behaviors should be comparable to those exhibited under conventional signal).	**Erratic or evasive steering maneuvers -** Compare incidence of these events to baseline condition. **Braking for vehicles in adjacent lane (includes sudden, hard braking events) -** Compare incidence of these events to baseline condition. Only applies to 460 routes (multi-lane roadway), with an adjacent vehicle.
Are the experimental braking signals annoying?	Previous static testing suggests that the experimental signals are tolerable to following drivers (as measured by glare ratings). The present study includes a set of "Annoyance" trails where the lights are triggered for an extended duration of 30 seconds with a following vehicle as a means to gauge annoyance.	Only applies to 460 routes (multi-lane roadway), with opportunity for passing. **Incidence of lane changes or passing (escape behavior) -** Compare incidence of these events to baseline condition. **Time course for inducing lane change -** (How long did drivers tolerate signal before initiating a lane change)? Compare time-course to baseline condition.

Approach

This effort was naturalistic; drivers were not recruited for the study. Rather, the research vehicle (equipped with the candidate lighting signals and driven by VTTI researchers) "coupled with" (merged in front of) vehicles in the available traffic stream to create naturally occurring Car-Following situations on two different types of roadways. The research vehicle's rear signals were manually activated under a set of pre-defined conditions during the drive. Signal activations were limited to low to moderate traffic densities and to situations that were deemed safe. It should be emphasized that activations were not tied to actual research vehicle hard decelerations; consequently, following driver reactions could be recorded in relative safety.

This method required two experimenters in the research vehicle: one to drive, and the second to trigger the brake lights manually under the appropriate conditions. To accomplish appropriate triggering, images from two rear-facing cameras with telephoto lenses were monitored by the second experimenter so that the gaze of the following driver could be determined in real-time (provided conditions allowed obtaining an acceptable image of the following driver's face). If the driver of the coupled vehicle looked away from the forward view, the experimenter would trigger the rear lighting. If the driver did not look away or the driver's face was undetectable, the second experimenter would trigger the lighting near the end of the run in any case. This situation provided data for the case where the driver was assumed to be looking forward; that is, the case most likely to occur.

The research vehicle was designed so that it would look very much like a production vehicle. Extreme care went into development of the redesigned taillight assemblies. Four round LED lamps were used in each outboard assembly, and three such units were used in the CHMSL. In regard to the outboard assemblies, two round LED units were installed in the rear fender portion and two were installed in the deck lid portion of a 2002 Cadillac Seville STS. The four lights operated together in a horizontal row, to form the outboard assembly. It should be noted that the static tests used six such round units, but there was simply not sufficient room to include them in the research vehicle without large modification to the vehicle. Since the vehicle was expected to be used for many other experiments at VTTI, the decision was made to use only four units. Of course the brightness of each individual unit could still be allowed to reach the same level as was used in the static tests.

The 2002 Cadillac STS had a production, wide, vertically thin CHMSL mounted in the upper edge of the trunk lid, which was disconnected. Because the vehicle itself was painted red, the production CHMSL could not be distinguished at ordinary following-vehicle driving distances. Therefore, there was no need to perform additional work to hide the production CHMSL. The re-designed CHMSL was one that fitted inside the vehicle rear window and was mounted on the package shelf. It was composed of three round LED units, as stated earlier.

Important modifications were made to each round LED unit (both for the outboard lamps and for the redesigned CHMSL). First, the red lens on each unit was machined away. In addition, the outer mounting lip was removed so that the units could be fitted closer together. The LEDs used in the round units emitted red light that was focused in a relatively narrow beam of approximately 7 deg. Thereafter, technicians at VTTI found an appropriate red, flat transparent lens material that could be sheet-molded to the same shape as the outboard lamps. The original lamp assemblies were then modified by removal of the incandescent lamps and installation of the round LED units. A new lens on each side was then custom-molded for each outboard lamp. These new red lenses had very small light losses because they passed the red light emanating from the LEDs. The new lenses also did not change the beam width to any appreciable extent, because light bending at the inner surface was compensated by opposite light bending at the outer surface. These red lenses looked very much like original equipment. Appendix D provides measured data regarding the lighting as installed in the lead vehicle.

The redesigned CHMSL was similarly constructed of round LED units with the red lenses removed. The three units used a single sheet of flat red lens material, which helped hide the units when they were not illuminated. As indicated the entire CHMSL was installed inside the rear window. Tests showed that the rear window was lightly tinted. Light output through the rear window was measured. Results are presented in Appendix D.

The drive electronics for all of the lamps produced the three conditions that were used in the experiment. These will be described in greater detail later, and included steady brake lamp level, flashing brake lamp level, and flashing emergency level (which was substantially brighter). Figure 37 shows the rear of the research vehicle with the rear lamps off, while Figure 38 shows the vehicle with the lamps illuminated at the emergency level. It is important to stress that every effort was made to create a research vehicle that looked almost identical to a production vehicle, so that there would not be a curiosity factor associated with the experiment. Figure 37 shows that indeed this was achieved, and that it would be very difficult to determine ahead of time that the research vehicle was not a production vehicle.

Figure 37. Research Vehicle With Rear Lighting Extinguished

Figure 38. Research Vehicle With the Rear Lighting Energized at the Emergency Level. (Lighting Was Subjectively "Redder" Than It Appears in the Photograph.)

A second research vehicle, called the confederate vehicle, was used to support the (first) research vehicle during this naturalistic data collection. The confederate vehicle was equipped with a forward view camera intended to record both the onset of the rear lighting in the research vehicle and the brake lights in the coupled (following) vehicle. The confederate vehicle followed the research vehicle and the coupled vehicle at a safe, non-interfering distance. Actually, the confederate vehicle had two important purposes: to record whether or not the driver of the coupled vehicle used his or her brakes, and to record any maneuvers or other driver behavior that might have been created by the research vehicle lighting activation. For those drivers who did use the brakes, reaction times were calculated (post experiment) using the recorded video. The study was run in the daytime and in dry weather conditions. The camera on the confederate vehicle was installed in front of the internal rear view mirror and aimed forward through the windshield. The experimenter driving the confederate vehicle was instructed to capture at least a portion of the (lead) research vehicle in the camera view, so that lighting onset could be determined. Figure 39 shows the front of the confederate vehicle. As can be seen, the vehicle appeared to be an ordinary vehicle.

Figure 39. The Confederate Vehicle Used to Obtain Video of the Research Vehicle's Lighting Activation and the Coupled Vehicle's Brake Lighting, if Activated

Experimental Design

Scenario (public roads used)

Two basic situations were examined. One involved driving on a U.S. highway (U.S. Route 460 near Blacksburg, Virginia) with two lanes in each direction, and the other involved a moderate speed State route (Route 114 in Christiansburg, Virginia) with only one lane in each direction. These two types of roadways were considered to be safe for the testing, while at the same time providing authentic data. The U.S. highway had posted speed limits of 55 and 65mph (88.5 and 104.6 km/h) where data was taken, and limited access with stretches quite similar to interstate highway. The State route was not limited access, but had long stretches with posted speed limits of 45 and 55 mph (72.4 and 88.5 km/h), with data gathering performed in the 45 mph (72.4 km/h) zones. On the U.S. highway, the lead vehicle (research vehicle) maintained a speed of 60 mph (80.5 km/h) for the in-lane trials, and 50 to 55 mph (80.5 to 88.5 km/h) for the adjacent lane trials. On the State route, the lead vehicle maintained a speed of approximately 45 mph (72.4 km/h).

Experimental Brake Signals

The rear lighting configurations evaluated in this study were determined by the results of the static tests as well as prudent comparisons. Of course, a baseline was included for purposes of comparison. For purposes of comparison, a signal was also tested at the normal brake lamp level, which is sometimes referred to as the Mercedes-Benz concept. The flashing frequency was 5.0 Hz. This is the frequency found to be optimal in earlier tests with flashing and increased brightness. Because it was considered unlikely that a different frequency would be optimal, the same flash frequency was used for the normal brake lamp level flashing signal. The third signal was one that was considered to have the overall best performance in terms of ratings and eye-drawing capabilities in earlier experiments. This signal flashed all lights at a 5 Hz frequency with increased brightness, that is, emergency brightness.

To reiterate, the three signals were:

1. **Baseline**. Baseline Braking Signal, constant on, at normal brake light level,
2. **Flashing w/o Increase**. Optimized Simultaneous Flashing of All Lamps with normal brake lamp level (no increase in brightness) (Mercedes-Benz type signal), and
3. **Flashing w/ Increase**. Optimized Simultaneous Flashing of All Lamps With Increased Brightness.

The third signal (optimized simultaneous flashing of all lamps with increased brightness) was found to provide the highest eye-drawing capability as determined by the static surprise event detection task, and was also a top-rated signal for perceived attention-getting (as determined by the subjective ratings data). The second signal (optimized simultaneous flashing of all lamps with *no increase in brightness*) demonstrated mild attention-getting characteristics, although its performance was well below the levels of the second signal. Nevertheless, it is was included because of its practical implications, given that it represents an approach currently being adopted by a major automotive manufacturer, and given that it applies the same signal characteristics as the aforementioned approach with the exception of increased signal brightness. It was anticipated that comparison between these two signals would highlight the relative impact of adding signal brightness. Figure 40 depicts the data that were gathered, while the measured specifications for the three signals tested appear in Appendix D. These measurements were made with the Cadillac STS that was used for the tests. The process took place in a dark laboratory so that accurate measurement of lamp output illuminance could be made. Note that since the lamps flashed for two of the signals, the measurements correspond to peak illuminance.

For the steady brake signal, the measurements are therefore the same as for the peak illuminance of the brake level flashing signal.

Exposures

There were 60 trials of a Car-Following scenario for each of the two road types and each of the three signal types as shown in Figure 40. This resulted in 360 replications in total. However, additional trials were also performed. To determine the effects of the lighting on "other drivers," that is, drivers in adjacent lanes, trials were performed on the U.S. route with the coupled vehicle in the adjacent lane. Note that in this condition, the confederate vehicle remained in the lane of the research vehicle. This test could only be run on the U.S. route because it had two lanes in each direction, unlike the State route that had only one lane in each direction. Again, 60 replications were obtained for each lighting configuration for a total of 180. Finally, "annoyance" runs were made. In this case, instead of having the rear lights activated for 5.0 s, they were activated for 30 s. The purpose of these runs was to determine how following drivers responded in terms of amount of annoyance the rear lighting created for the following driver. In all, 45 replications were made for this situation, again, only on the U.S. route. Here the idea was to allow drivers to escape by changing lanes and passing, or changing lanes and slowing. This could only be accomplished safely on the U.S. route and only when there was no traffic nearby, particularly in the adjacent lane.

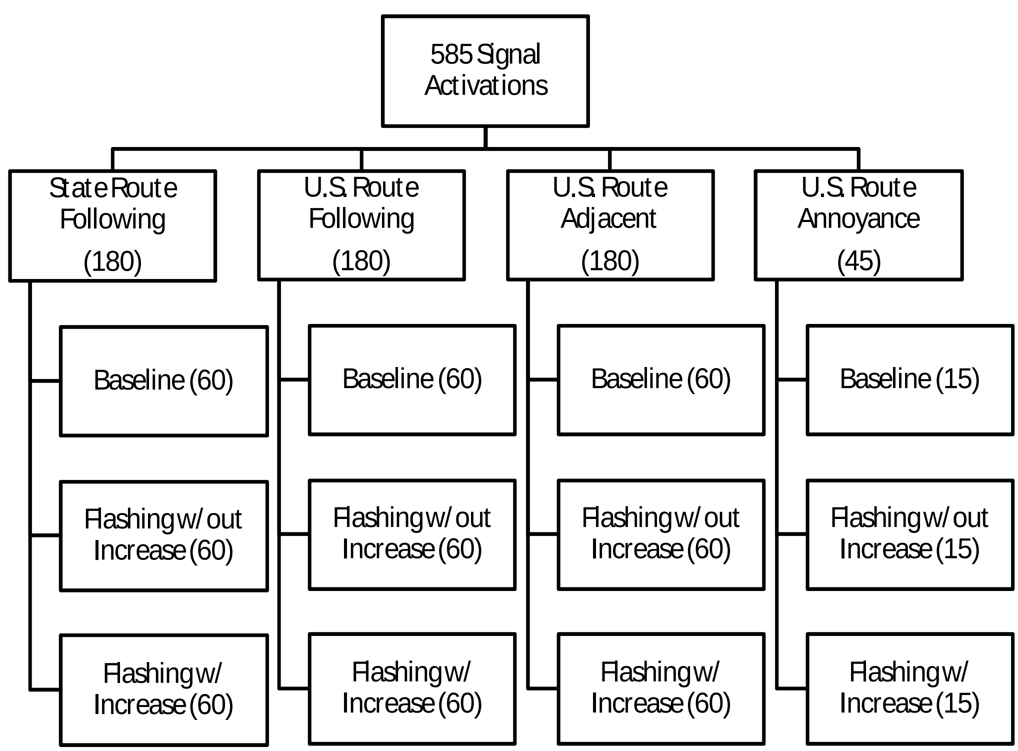

Figure 40. Layout of the Brake Signal Experiment.

Distances Between Vehicles

The experimenters in the two research vehicles (research vehicle and confederate vehicle) attempted to maintain uniform spacing at the time of activation of the rear lighting. However, variation remained because of experimenter reaction time and because the coupled vehicle was not under control of the experimenters. Generally speaking, activation occurred when the distance between the rear bumper of the research vehicle and the front bumper of the coupled vehicle was between 40 and 80 ft (12.2 and 24.4 m). In regard to the confederate following vehicle, it remained at an estimated distance of 100 to 150 ft (30.5 to 45.7 m) behind the research vehicle, and as indicated, it always stayed in the same lane as the research vehicle.

Vehicle Instrumentation and Data Collection

In addition to the system producing the three lighting configurations, the research vehicle was equipped with a modified 100-Car data collection system, to capture and record relevant data and rear lighting system state. The primary means of data collection was via cameras. As indicated, the research vehicle included two rear facing cameras to capture (to the extent possible) detail relating to following driver's head and glance direction associated with light activations. Results from previous on-road work (Lee, Llaneras, & Wierwille, 2005) suggested that use of rear-facing video would be effective for this purpose. The two cameras used long focal length lenses (and the same zoom levels) to capture the following driver's head and eye movements; each camera had a 4 degree field of view. The two cameras were aimed in slightly different directions so that the total field of view was approximately 7 degrees.

Video was recorded prior to and during activation of the rear lighting by the second experimenter in the research vehicle. The video was then used to record the coupled vehicle driver's face, if possible. The video also contained a code that indicated time and state of the rear lighting, that is, active or not active. The confederate vehicle, which followed the coupled vehicle at a distance, recorded the rear lights of both, the research vehicle and the coupled vehicle on video, as well as any maneuvers the coupled vehicle performed.

Data Reduction and Analysis

Video captured during signal activations was reduced and analyzed to assess the effects of the rear lighting signals, if the driver was looking away. If the driver was not looking away or eye glance direction could not be confirmed, the video was used to examine driver reaction in terms of braking or other driver behavior. Each episode was analyzed to document whether the following vehicle driver was glancing away from the forward roadway preceding the activation, and if so, to determine the length of time before the driver re-directed his or her gaze to the forward roadway following activation of the brake signals. Key measures provided by the instrumentation included:

- Video to capture the following driver's face and head movements;
- Rear lighting system state (e.g., active or not active);
- Time duration from research vehicle brake light activation until the driver of the coupled vehicle looked forward, following a glance away from the road;
- Time duration from research vehicle brake light activation until the driver of the coupled vehicle began braking or performed other observable maneuvers (e.g., lane changing or erratic driving, such as weaving); and
- Classification of coupled vehicle maneuver in response to rear lighting activation.

Special Considerations and Qualifications

This approach was unique and intended to provide naturalistic data regarding driver reaction to the three rear lighting configurations. It was understood from the outset that the experimental methods used were largely untried and might result in situations in which sufficient data, such as eye drawing capability, could not be gathered. The experiment took place during late July and early August 2008. As a result, skies were near their brightest because of high sun angles in summer. Data was collected over a period of approximately 4 to 6 weeks.

Analysis and Results

Eye-Drawing

The study design called for a total of 360 car-following situations, with the goal of capturing 60 eye-drawing instances (20 in each of the three lighting conditions) where the brake signals were triggered while the following driver's gaze was off-road. Figure 41 subdivides the available number of reduced and usable car-following and eye-drawing cases. Although many triggers were issued in the field, the number of usable eye-drawing cases was limited; some cases were simply erroneous events (where the in-vehicle experimenter thought the following coupled driver was looking away). This underscores the relative difficulty of capturing these types of events. As a result, relatively little data were gathered over the course of the roadway evaluation trials to allow eye-drawing effects to be determined reliably. Although the data collection system enabled the following driver's eye-state to be assessed (looking forward or off-road), few usable cases were captured wherein the braking signal was triggered while the driver was looking away from the forward roadway (this occurred despite concerted efforts to capture these events). In other words, these cases proved to be rare events. Nonetheless, limited eye-drawing data were available and are presented here.

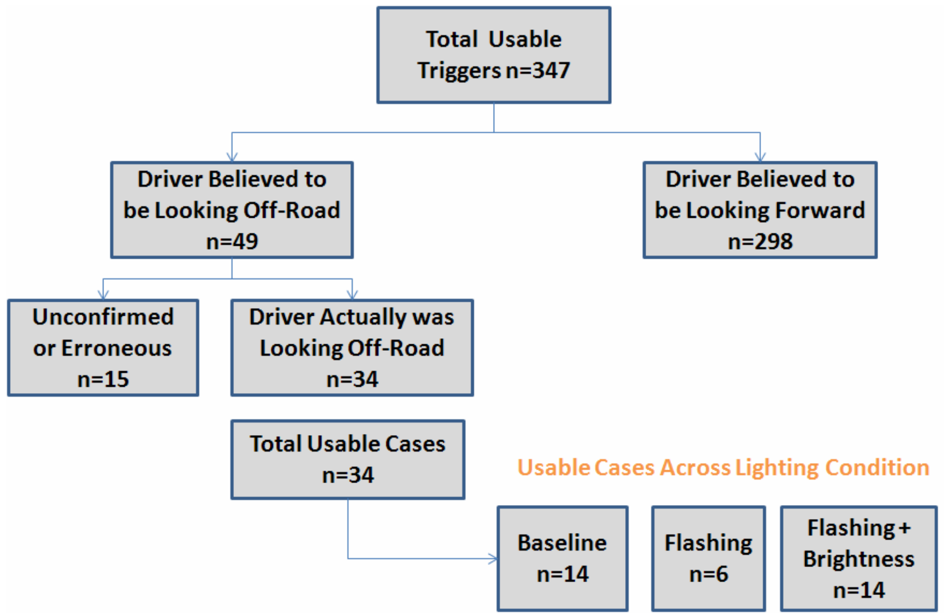

Figure 41. Breakdown of Available Car-Following and Eye-Drawing Cases

As shown in Figure 42, slightly less than 10 percent of the available car-following cases (34 out of 346) provided opportunities to assess the eye drawing effects of the signal. Cases were distributed over the three signal conditions yielding a total of 14 baseline cases, 6 flashing cases, and 14 flashing with increased brightness cases (Figure 41).

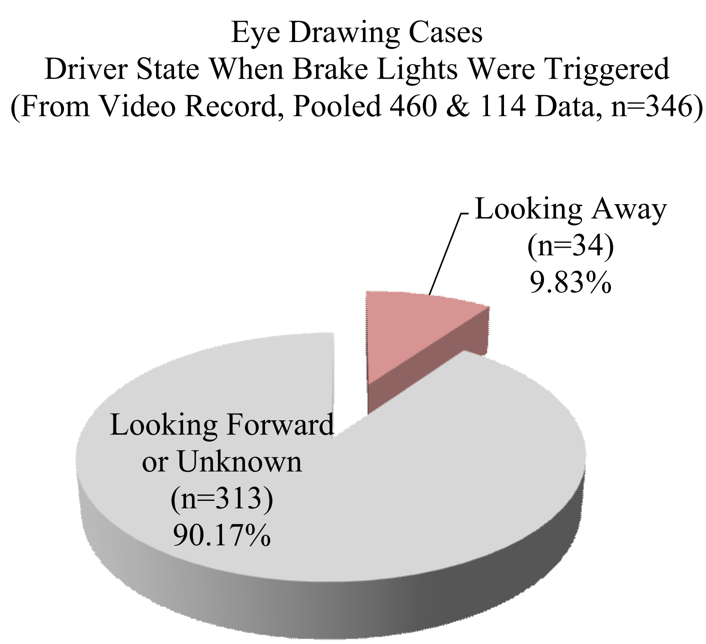

Figure 42. Percentage of Cases Captured Where Drivers Were Observed to Be Looking Away at Signal Onset (Available Eye-Drawing Sample)

It is important to stress that these sample sizes are small compared to previous eye-drawing evaluation efforts (recall the controlled test track study conducted by Wierwille et al., 2005 used a sample of 72 drivers, 24 in each of three lighting conditions). Moreover, the 34 cases were captured in a completely naturalistic setting so the nature of the off-road glances (purpose, direction, eccentricity from the forward roadway, etc.) were uncontrolled and random, thereby increasing variability in the data set and making it difficult to study eye-drawing effects.

Figure 43 shows the mean eye-drawing latencies (time from brake light illumination to the driver's glance back to the forward roadway) across lighting conditions. These values represent the time, on average, it took drivers to redirect their glances to the forward roadway following brake signal activation. Several observations are noteworthy:

Response latencies are quite small averaging 457 milliseconds (0.457 s) across all of the lighting conditions. In fact, 25 percent of the cases had response latencies at or below 200 milliseconds (0.20 s). These are likely too small to be considered responses to the signals. Signal activations in this setting were not necessarily co-incident with the driver's initial glance off-road; they may have occurred sometime well into the off-road glance epoch. In other words, it is possible that in these instances the signal lights may have been triggered sometime after the driver's initial glance from the forward roadway at a point where drivers may have already started the process of looking back to the forward roadway. This would account, in part, for some of these very low response times;

On average, both of the experimental signals show a tendency for faster eye-drawing relative to the baseline braking signal. However, these differences are very small and not statistically significant. Note that the number of cases for the flashing condition is extremely small.

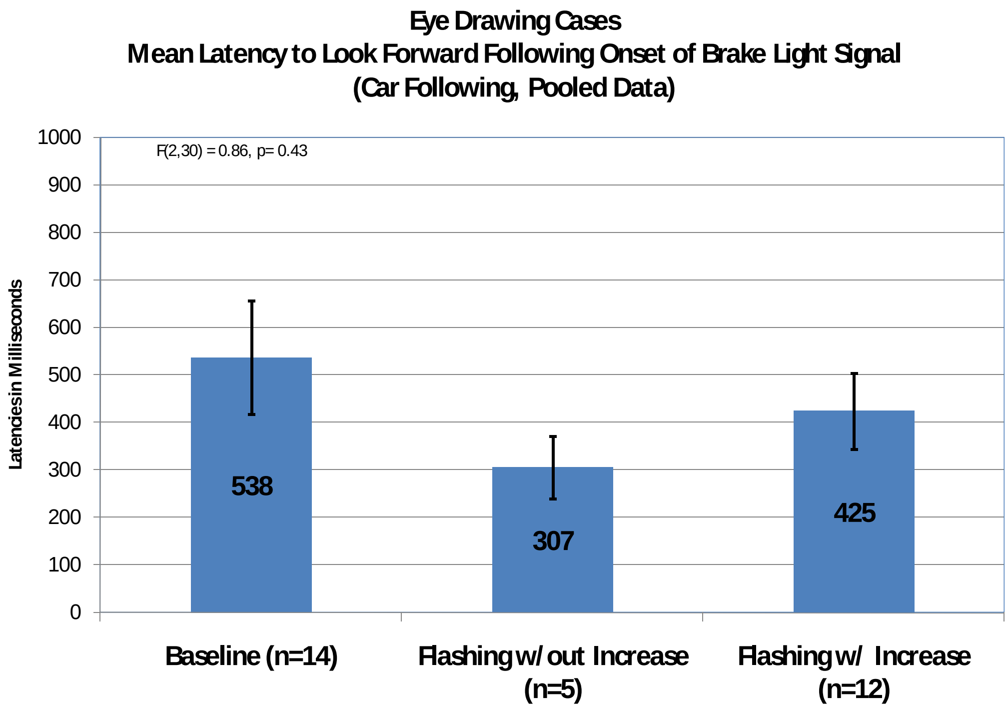

Figure 43. Mean Response Latencies Across Lighting Condition (Eye-Drawing, Car-Following, and Pooled Data)

Even with this relatively small dataset, some evidence does exist to suggest that the Flashing With Increased Brightness signal is effective at redirecting the driver's gaze forward, curtailing or limiting the duration of off-road glances. Evidence for this is found by examining the distribution of glance latencies following activation of the signal (i.e., the time interval from signal activation to drivers' glance back to the forward roadway). Figure 44 plots these glance distributions for the baseline and the Flashing With Increased Brightness conditions (the lashing-only condition is not presented because the sample size was too small to generate a reliable distribution). As shown in the figure, the extreme tail of the distribution differs somewhat between these two conditions; for example, over 20 percent of the drivers in the baseline condition (3 out of 14) yielded latencies over 1 s, while none of the drivers in the experimental condition (Flashing With Increased Brightness) were observed to have glance latencies over 1 s. These data suggests that the Flashing With Increased Brightness condition appears to benefit drivers by compressing the tail of the distribution, reducing the occurrence of long off-road glances.

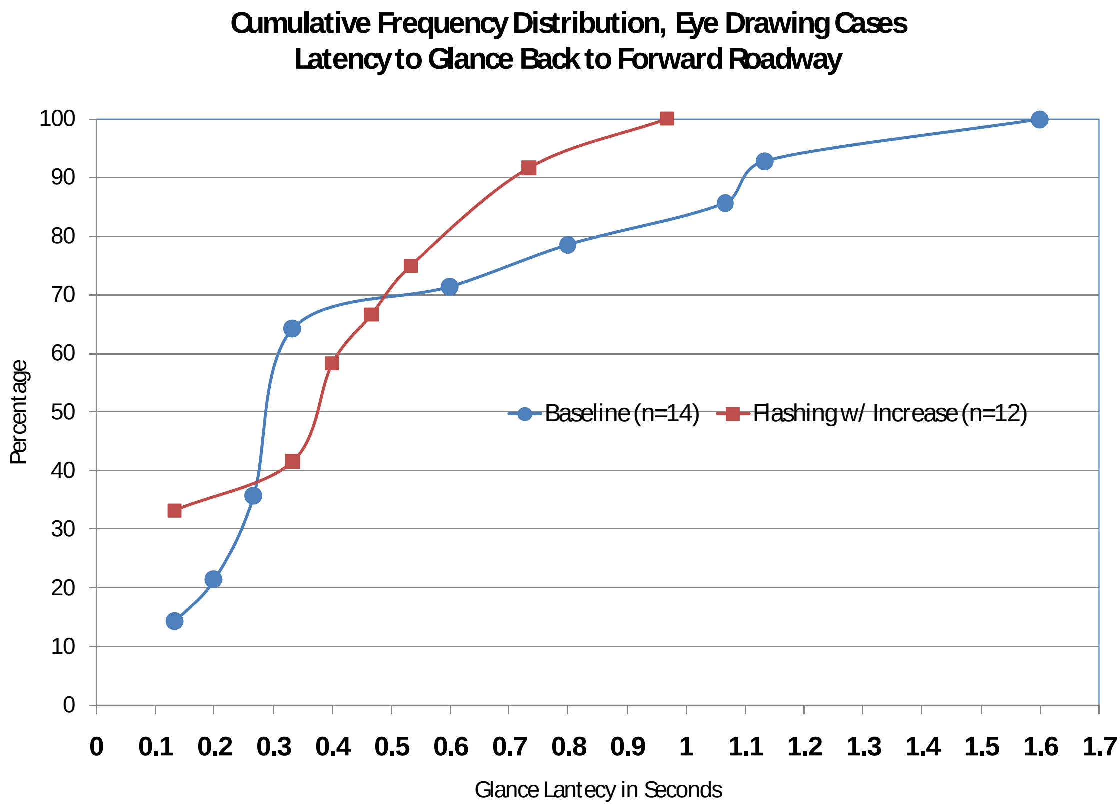

Figure 44. Cumulative Distribution of Response Latencies for Baseline and Flashing With Increased Brightness Condition (Eye-Drawing Case)

Driver Behavior (Braking Response)

This section explores the impact of the experimental lighting signals on driver braking behavior for Car-Following situations. Unlike the previous section, cases are not limited to those in which the following driver is observed to be glancing away from the forward roadway, but include situations where following drivers are looking forward. This analysis was intended to assess the degree to which the experimental signals evoke a braking response.

Braking was not the predominant behavior following the onset of the research vehicle's brake lights (this is not necessarily unusual since the lead vehicle did not actually decelerate and therefore cues related to deceleration were not present). As shown in Figure 45, only about one-third of drivers (33%) were observed to brake as measured by illumination of the subject vehicle's brake lamps. Note that it is possible that drivers did exhibit other forms of precautionary behaviors (covered the brake, etc.), but these were not overtly visible or measurable. The relatively small number of braking cases is not surprising because the research vehicle did not actually decelerate or slow to create a difference in the closing distance between the vehicles. Drivers were only responding to the activation of the research vehicle's brake lights alone, independent of lead vehicle deceleration.

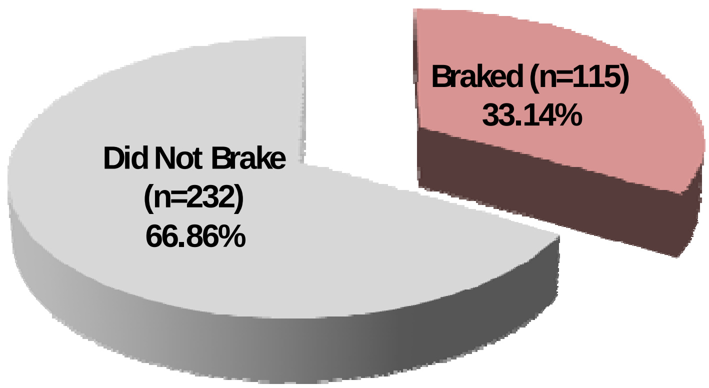

Figure 45. Percentage of Drivers Observed to Brake or Not Brake in Car-Following Situations (Pooled U.S. and State Route Car-Following, n=347)

The pattern of braking responses across the three lighting configurations revealed a significant relationship between signal type and braking [$\chi^2(2) = 6.44$, $p< 0.039$]. The highest incidence of braking response was associated with the Flashing With Increased Brightness condition with 39 percent of the drivers observed to brake in response to the signal (Figure 46). In contrast, approximately 25 percent of drivers exposed to the Baseline signal were observed to brake. Thus, the enhanced signal (Flashing With Increased Brightness) significantly increased braking response over the conventional signal [$\chi^2 (1) = 5.95$, $p< 0.015$]. No statistically significant differences resulted between the two experimental conditions (Flashing Alone and Flashing With Increased Brightness), or between the baseline and Flashing Alone condition.

These results suggest that the Flashing With Increased Brightness signal appears to be a powerful cue, in many cases evoking a braking response independent of actual lead vehicle deceleration. Since the research vehicle was not actually decelerating (the braking signal was decoupled from actual vehicle deceleration), this signal essentially took precedence over looming cues (or lack thereof) received from changes in closing distance associated with actual deceleration. While Flashing Alone was also found to increase the incidence of braking responses, the increase was not significantly different from the conventional signal approach.

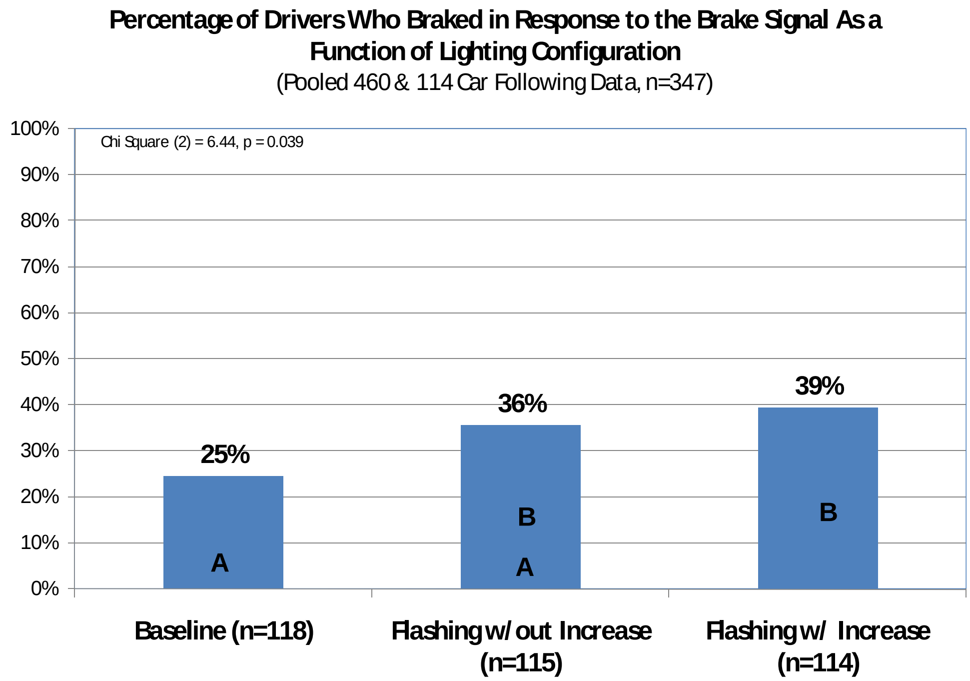

Figure 46. Percentage of Drivers Observed to Brake in Response to the Brake Signal as a Function of Lighting Condition (Pooled U.S. and State Route Car-Following, n=347)

Interestingly, the incidence of braking was found to increase dramatically for drivers who were observed to be glancing off-road when the research vehicle's brake lights were activated. As shown in Figure 47, upwards of 60 percent of drivers exposed to the experimental brake signals while looking away were observed to brake when their gaze returned to the forward roadway. As mentioned above, the Flashing With Increased Brightness condition significantly increased braking responses [$\chi^2(1) = 4.66$, $p< 0.03$], increasing levels from 21 to 64 percent. Thus, the Flashing With Increased Brightness signal appears to be particularly effective under situations where the following driver is looking away from the forward roadway (distracted), prompting a braking response once the driver redirects vision forward. Again, Flashing Alone was found to increase braking incidence, but this result was not statistically significant (likely due to the small sample size).

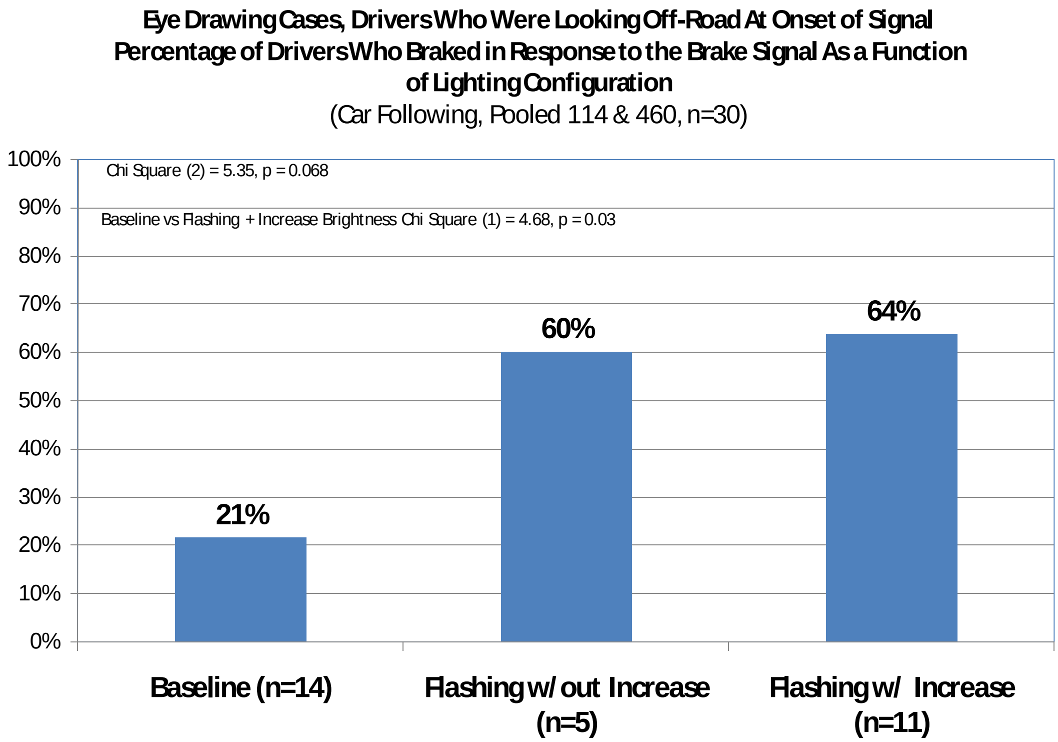

Figure 47. Percentage of Drivers Who Braked in Response to the Brake Signal as a Function of Lighting Condition for Drivers Who Were Glancing Away at Signal Onset (n=30)

Brake Reaction Time

Brake reaction time data were also taken for drivers who braked in response to the research vehicle's brake signals. These data are presented for pooled cases (all available routes) as well as for the state route individually since expectancy and preview for braking events are anticipated to be different between the routes. When all data are pooled, no statistically significant differences in brake reaction times were observed across the three lighting conditions [F(2,103) = 0.69, p = 0.5054]; however, as illustrated in Figure 48, mean brake reaction times did tend to decrease slightly with the application of the experimental braking signals. Of particular note is the reduction in the standard error associated with the Flashing and Flashing With Increased Brightness signals.

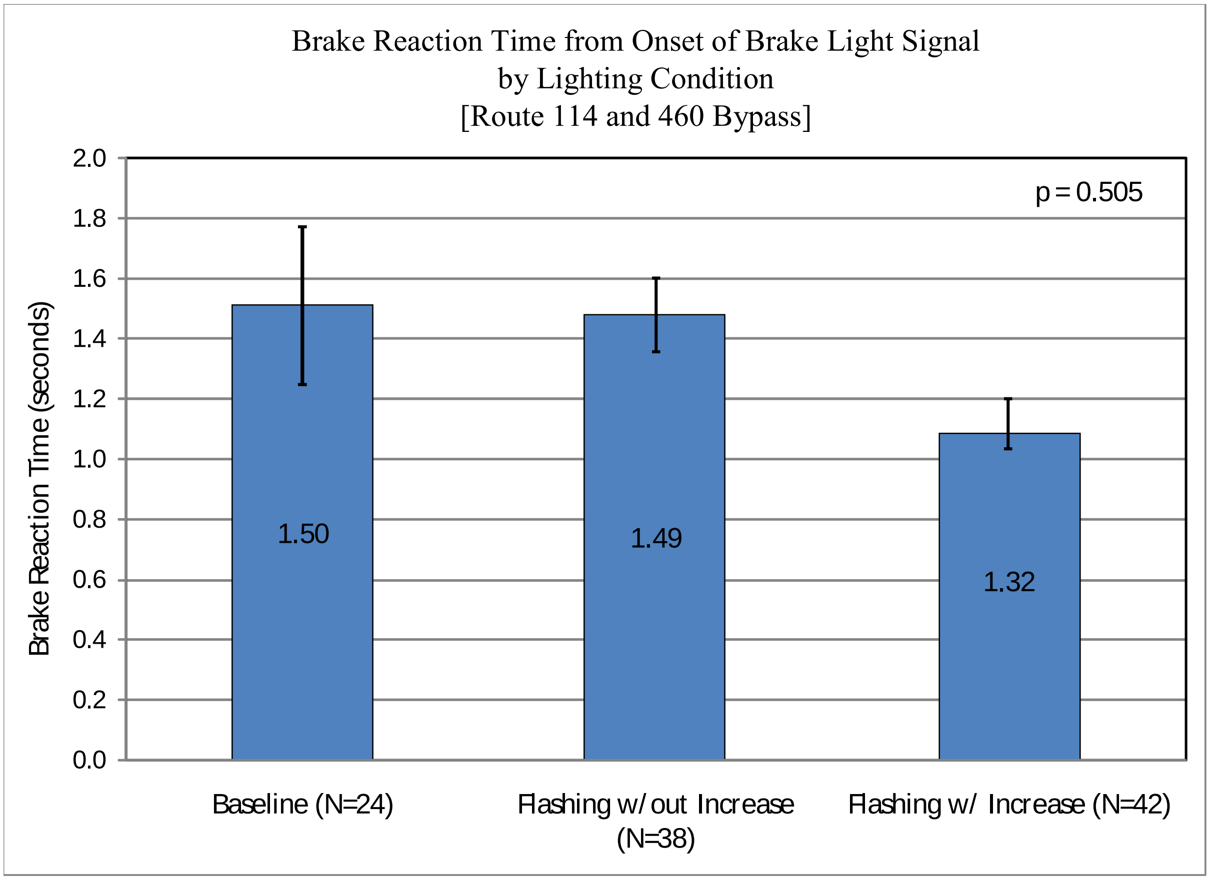

Figure 48. Mean Brake Response Times Across Lighting Condition (Pooled State and U.S. Route Car-Following Data)

Differences in brake reaction times are magnified somewhat when response time data are isolated for the state route (single lane rural road), but differences still do not reach significance [$F(2,68) = 1.40$, $p = 0.2536$]. As shown in Figure 49, the Flashing With Increased Brightness signal shows an average reduction of 0.32 s (320 milliseconds) in brake response times relative to the baseline signal.

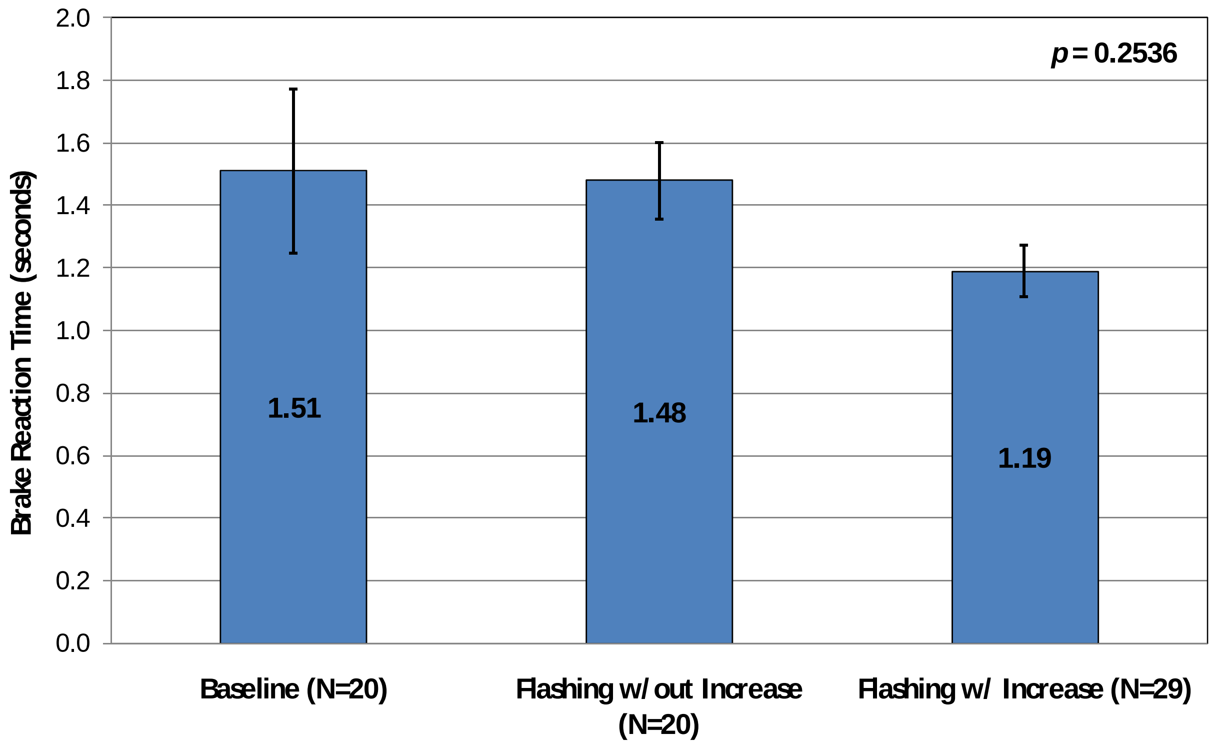

Figure 49. Mean Brake Response Times Across Lighting Condition (State Route Data Only)

Response time data are also presented as a cumulative frequency distribution. Pooled distributions (combined State and U.S. Routes) show all three signals are closely aligned, but do reveal some differences, particularly between the baseline and flashing without increase (Figure 50). Note the single outlier in the baseline condition. Examination of the distribution of brake reaction time data limited to State Route cases shows a clearer distinction among the lighting conditions, particularly for the Flashing Alone signal. As illustrated in Figure 51, the distribution of braking reaction time under the Flashing Alone condition tended to be shifted to the right relative to the other signals, suggesting somewhat slower braking response times. This may indicate that drivers were more tentative in their braking decisions under the Flashing Alone condition, compared to the conventional brake signal or the Flashing With Increased Brightness signal.

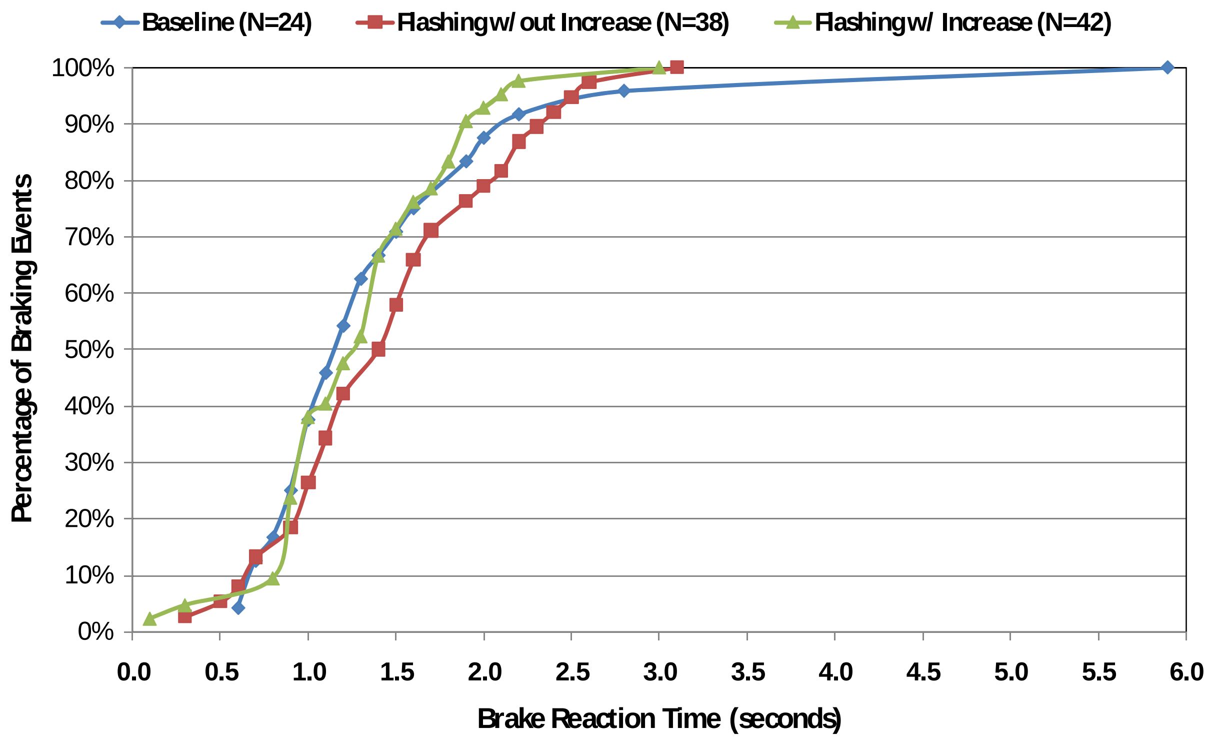

Figure 50. Cumulative Distribution of Brake Response Times (Pooled for State and U.S. Route Data)

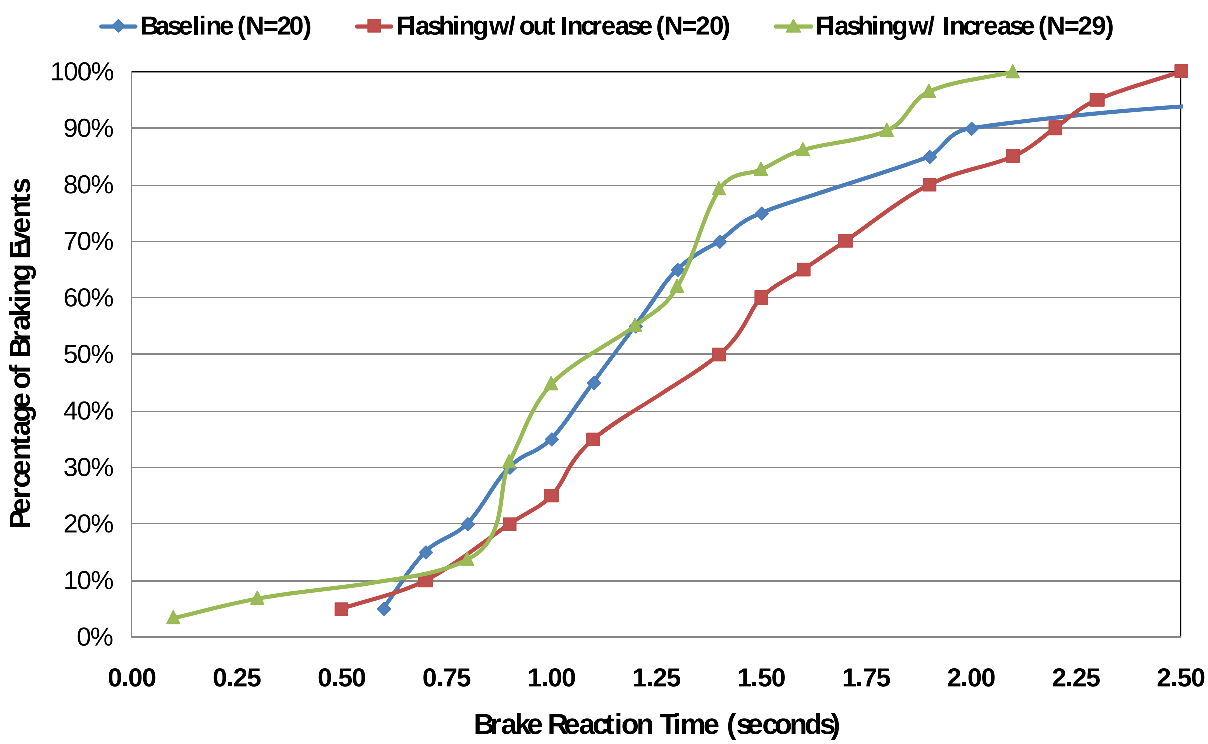

Figure 51. Cumulative Distribution of Brake Response Times (State Route Data Only)

Unintended or Undesirable Behaviors

This section presents data that provides insight into potential unintended consequences associated with the experimental signals, including the incidence of braking responses from traffic in the adjacent lane as well as erratic or undesirable behavior from following vehicle drivers.

Impacts on Adjacent Traffic

Rear signals used in this study were specifically designed to be attention-getting, that is, to alert following drivers of lead vehicle hard braking events. Baseline signals were also developed for purposes of comparison. Signals were directionally tuned using LED technology to be most visible directly behind the vehicle and less so to surrounding traffic in the adjacent lanes (refer to Table 1 and Table 4 for Field of View information). One issue explored as part of this roadway evaluation was the extent to which the brake signals, shown to be attention-getting, would induce braking responses from vehicles in the adjacent lane. Data bearing on this issue (captured on the U.S. Route) are presented in Figure 52 (note cases are limited to situations where the adjacent vehicle was located between 40 and 80 ft from the research vehicle). These data show that both experimental signals (flashing and flashing with increased brightness) increased the incidence of adjacent vehicle braking events. Under the baseline signal, less than 2 percent of drivers braked (1 out of 57 drivers). However, this percentage increased to 12 percent for the Flashing condition, and 20 percent for the Flashing With Increased Brightness signal. Both increases were statistically significant, differing from the Baseline treatment [$\chi^2(2) = 9.43$, $p<0.008$]. These data suggests that the introduction of these new signals (as currently implemented on this vehicle) would likely increase braking responses for traffic in the adjacent lane; this may be a concern worthy of further exploration and verification. It is important to note that the reason underlying this behavior is not known (drivers could have been acting cautiously in response to these novel signals, not wanting to pass the research vehicle, or slowing due to curiosity). In any case, the brightness of the signals as viewed from an adjacent lane is known to be substantially less than in-lane brightness. This result is based on the narrow beam width of all the signals used in the experiment, including baseline.

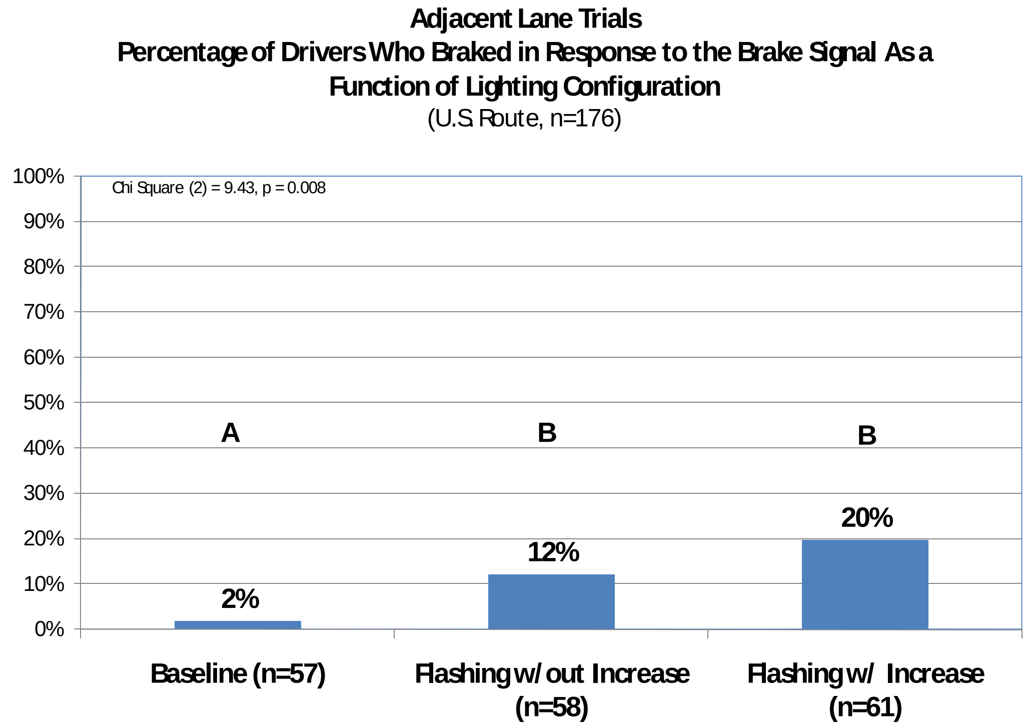

Figure 52. Percentage of Adjacent Vehicle Drivers Observed to Brake in Response to the Signal (U.S. Route).

<u>Erratic or Undesirable Behaviors</u>

Responses to the brake lighting were evaluated in order to better understand the incidence of erratic or undesirable behaviors on the part of following vehicle drivers as well as vehicles in the surrounding traffic stream. These assessments were strictly subjective in nature made by in-vehicle observers who judged whether vehicles braked excessively or swerved in the lane following the onset of the brake signal. Relatively few instances of erratic or undesirable behaviors were observed under any of the lighting conditions, both for car-following and adjacent-lane trials. Nevertheless, as shown in Figure 53, some drivers in car-following situations were judged to respond to the braking signals with potentially undesirable actions including excessive braking (i.e., harsh sudden braking) and swerving (i.e., sudden steering corrections characteristic of an avoidance maneuver). Comparable results were found for adjacent-lane trials (Figure 54), where the most frequently occurring behavior of concern was aborting a passing maneuver. No conclusive evidence was captured as part of this study to suggest that these experimental lighting treatments pose a hazard or are more dangerous than conventional rear lighting designs. None of the observed reactions resulted in a near-crash situation; drivers did not swerve out of their lane boundaries, nor did braking responses appear to create a rear-end crash situation. Nevertheless, the fact that some unexpected behaviors did occur raises some concern and should be studied further to understand the locus and extent of these behaviors.

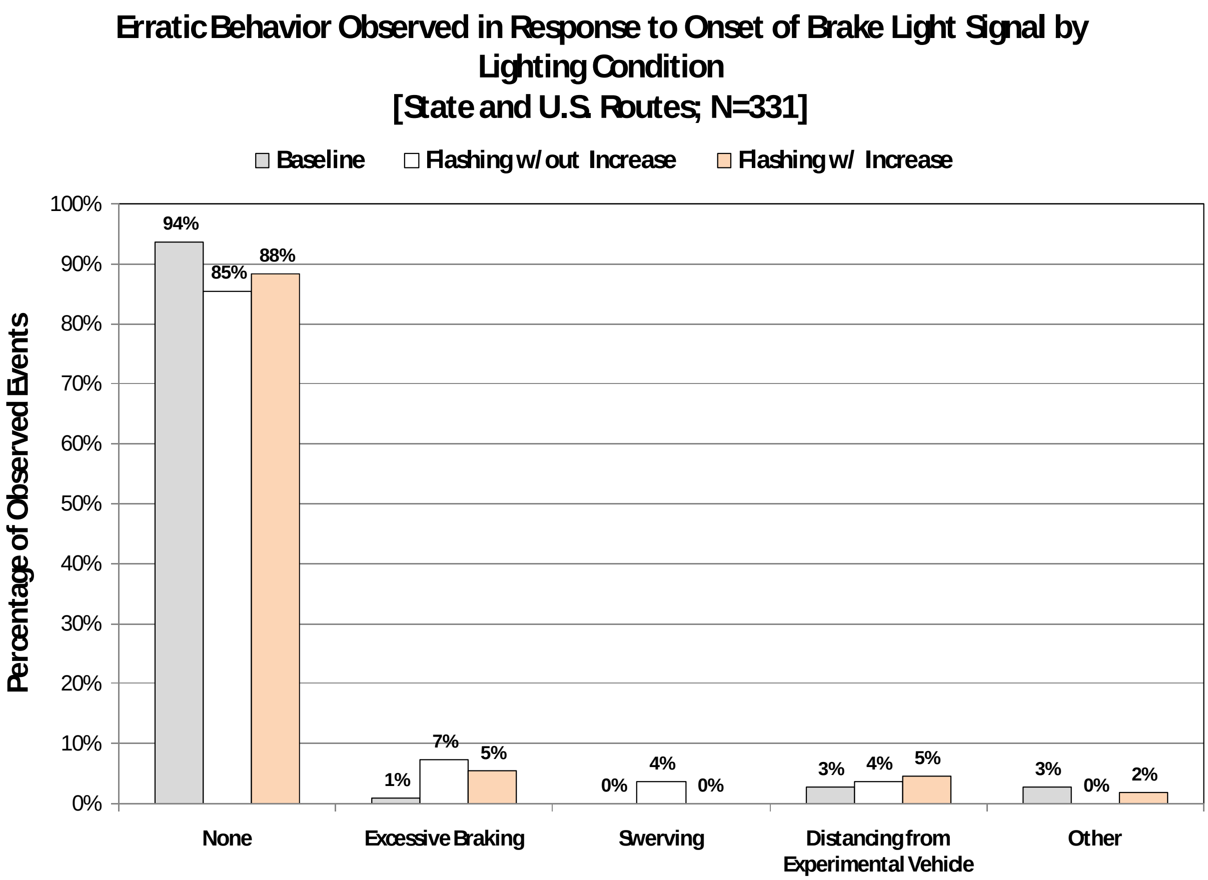

Figure 53. Incidence of Erratic Behaviors (Pooled State and U.S. Route Car-Following, n=331. Does Not Include Adjacent Vehicle Trials Data.)

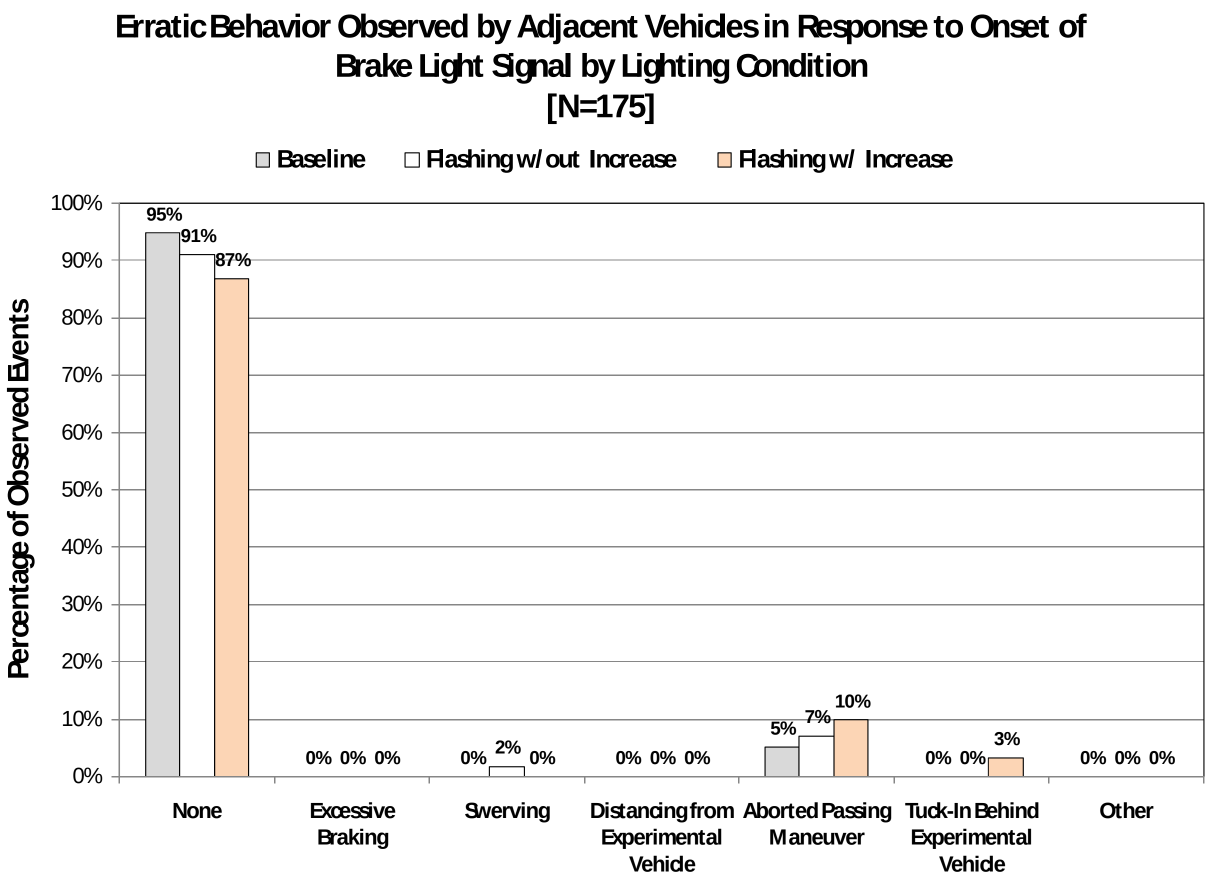

Figure 54. Incidence of Erratic Behaviors for Adjacent Lane Trials (n=175)

<u>Annoyance</u>

This section presents the results of a set of "annoyance" trials in which the brake signal remained activated for a period of 30 seconds during Car-Following episodes. Previous static tests found that the experimental signals were tolerable to drivers during a 5 s exposure (as measured by glare ratings). These trials were conducted in order to further estimate signal annoyance, and were performed dynamically on the U.S. route by exposing following drivers to prolonged signal exposures and affording them the opportunity to escape by passing or changing lanes. The underlying logic would suggest that overly annoying signals would lead drivers to change lanes or pass the research vehicle rather than remain exposed to the "annoying" stimulus. As shown in Figure 55, the vast majority of drivers (in either experimental signal condition) did not pass, nor did they change lanes during the 30 second exposure. In fact, the incidences of passing and lane changes under the experimental signals were reduced relative to the baseline situation. This suggests that these trials were not measuring "annoyance" per se. The vast majority of drivers exposed to the Flashing With Increased Brightness condition (57%) tended to slow or decelerate in response to the signal as opposed to pass or change lanes, actions more suggestive of cautionary behavior than annoyance. However, it could be argued that drivers decelerated to distance themselves from the signals.

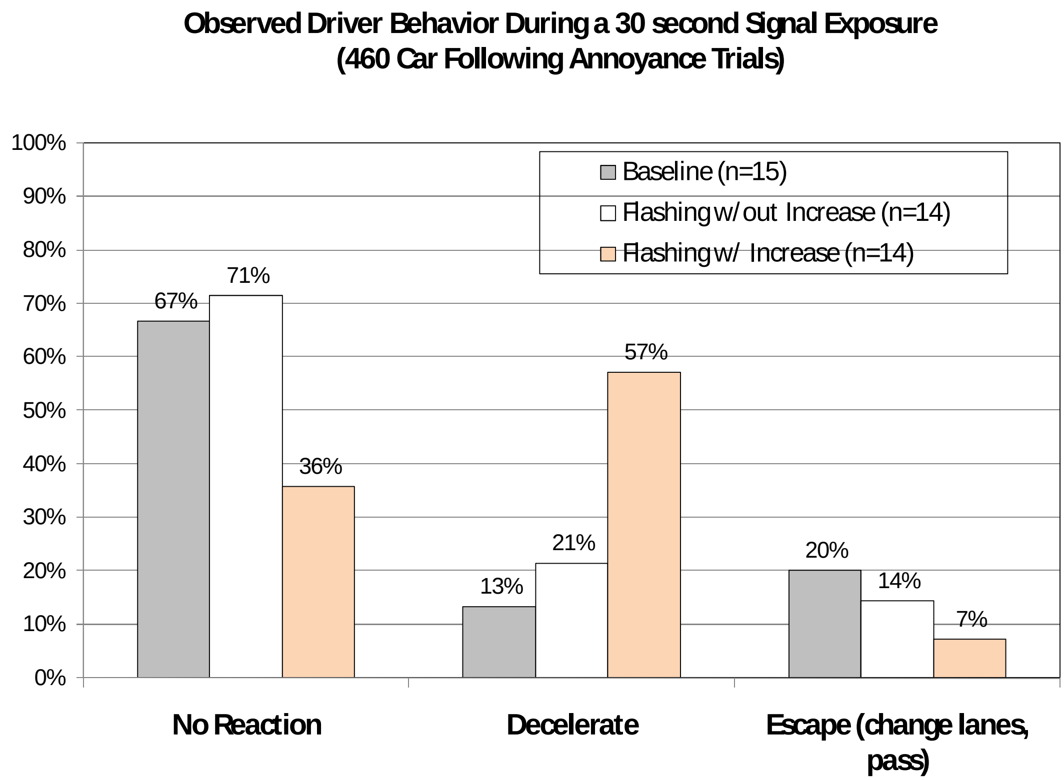

Figure 55. Observed Driver Behavior During the 30 s Signal Exposure Trials

Summary of Key Findings

Key findings derived from the roadway evaluations include the following:

- Cases where the following vehicle driver was looking away were extremely limited making it difficult to draw reliable conclusions regarding the attention-getting and eye-drawing properties of these signals. Nevertheless, distributions of glance latencies suggest that the Flashing With Increased Brightness signal may be effective at reducing the incidence of long off-road glances.
- Drivers exposed to the Flashing With Increased Brightness signal were more likely to brake in response to this signal compared to the conventional signals. This suggests that the signal is a powerful cue, evoking a braking response independent of lead vehicle

deceleration. Braking responses (for both experimental signals) were even more pronounced under conditions where the following driver was found to be looking away from the forward roadway at the onset of the braking signal. In both cases, drivers appear to be interpreting this cue as a braking signal.

- Mean brake response times yielded no substantive differences among the lighting conditions. However, the distribution of braking responses did reveal some minor shifts in the pattern for the Flashing Alone braking signal.

- Both experimental signals were found to increase the incidence of braking by vehicles in the adjacent lane. Additional work may be needed to further understand this behavior. Aside from this, relatively few instances of undesirable or erratic behaviors were observed, including instances of overly aggressive braking and aborted passing maneuvers.

- Despite attempts to quantify signal annoyance, little meaningful information was captured to address this aspect. Drivers did not appear more likely to pass or change lanes under the experimental signals, and those exposed to the Flashing With Increased Brightness signal tended to decelerate. This appears to be cautionary behavior or behavior intended to increase the distance between the vehicles.

Chapter 5. Refined Triggering Criteria for Open-Loop Enhanced Rear Lighting

Introduction

While development of an enhanced rear lighting system is heavily dependent on the rear lighting and signaling itself, the system is also dependent on other important factors. One of these is addressed in the current chapter, namely system triggering. There are several considerations in regard to determining trigger criteria and special cases for open-loop enhanced rear lighting. Open-loop systems, as previously defined, use parameters available in the lead vehicle only, that is, they do not include distance and closing rate to the following vehicle, which could possibly be obtained by radar, laser, or similar technology. Open-loop systems have the goal of providing triggering of the rear lighting when it is needed to help avoid a rear-end collision. At the same time, open-loop systems have the goal of *not* triggering when there is no real threat of a rear-end collision. These latter cases, if too numerous, could cause following drivers to ignore or neglect the rear lighting. Following drivers could also become annoyed by the nuisance of such lights when they are not needed.

In the original study performed at VTTI on rear lighting, researchers equipped a car with an accelerometer and drove it in traffic (Wierwille et al., 2005). They found that a deceleration on flat road of 0.35 g separated light and moderate braking from heavy breaking. They therefore recommended a trigger criterion of 0.35 g deceleration. They also recommended that once the enhanced rear lighting was triggered, it should continue until deceleration dropped to below 0.15 g and an additional 4 s of timeout had passed. The timeout was used to account for the fact that the lead vehicle would probably be moving slowly or standing on the pavement after the heavy deceleration. Later work at VTTI resulted in the recommendation that the timeout should be increased to 5 s. Thus, at the completion of the first research study, the criteria recommended for open-loop systems were as follows:

Trigger the enhanced rear lighting signal whenever deceleration of the equipped vehicle reaches 0.35 g or more. Continue the enhanced rear lighting signal until deceleration falls below 0.15 g and then continue for an additional 5 s after that.

These criteria seemed to work well and were in almost perfect agreement with later results from the statistical analysis of the 100-Car study (Lee, Llaneras, Klauer, & Sudweeks, 2007). One of the conclusions of that study was as follows:

Data suggest that a deceleration threshold of 0.4 g and above would serve as a viable triggering criterion for the onset of an enhanced rear-signaling system. Almost all crashes and near-crashes were above this threshold, while very few of the baseline braking events reached this threshold. This criterion, backed by the 100-Car data, is quite close to the 0.35 g criterion proposed in the original study, and that was based on engineering judgment and deceleration tests.

Consequently, on completion of the earlier studies, it appeared that a triggering threshold of 0.35 to 0.40 g was appropriate.

Three other problems surfaced during the earlier studies. One of these was the “uphill-downhill problem.” This problem occurs because the accelerometer used to measure the deceleration is usually “strapped down,” that is, it is attached along the longitudinal axis and therefore measures an additional gravity component whenever the vehicle goes uphill or downhill. This additional component will cause a shift in the equivalent threshold at which the enhanced rear lighting would be triggered.

Another problem encountered was that of continuing the rear lighting with a timeout segment when the vehicle turned at a corner. In this case a new following vehicle might be encountered and the driver of that vehicle might be confused by the activation of the enhanced rear lighting.

The final problem encountered was caused by the accelerometer itself. If the bandwidth of the device is too wide, the accelerometer output may appear quite noisy as a result of vehicle vibrations and roadway irregularities. This noise could easily reach the trigger threshold, in which case, the enhanced rear lighting might be initiated inadvertently.

Another proposal that has been suggested independent of the work at VTTI is to trigger the enhanced rear lighting using the anti-lock braking system (ABS) signal. The concept is that when ABS is activated, the vehicle is undergoing either high-g deceleration or skidding, both of which should be used to warn the following driver.

The three additional problems plus ABS activation are taken up in the following sections of this chapter. Solutions are then proposed that appear to provide the best performance without substantially increasing inappropriate triggering. These criteria could be further modified or refined after additional tests. The additional solutions are incorporated in a revised triggering system that is presented in the last section of this chapter.

Uphill-Downhill Problem

As stated, this problem occurs whenever an equipped vehicle brakes on either an uphill or downhill grade. If a following vehicle is going downhill, the situation is as shown in Figure 56. The weight of the vehicle, W, is straight downward, but the component of weight normal to the road, N, is reduced somewhat. Similarly, a component of the weight, F_W, contributes a forward force that is in the direction of the downhill slope.

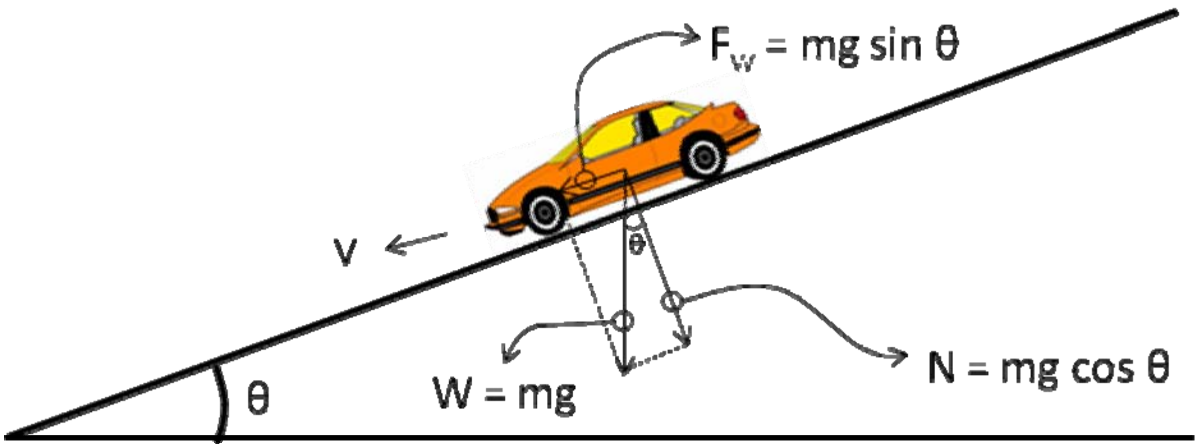

Figure 56. Forces on a Vehicle Created by a Downward Slope

If it is assumed that the brakes and tires create an equivalent constant coefficient of friction, then the braking force can be specified as

$F_D = \mu mg \cos\theta$, where μ is the equivalent coefficient of friction.

In this equation, m is the mass of the vehicle, g is the acceleration due to gravity, and θ is the downward inclination angle. F_D is a force acting upward along the incline responsible for the deceleration of the vehicle. Therefore the deceleration of the vehicle is

$$mg \sin\theta - \mu mg \cos\theta = ma$$

and a is the acceleration of the vehicle. Dividing through by m, it becomes clear that the deceleration is reduced by two components: the component of weight that is downward along the incline, and the fact that the force normal to the incline is reduced by the cosine of the angle of the incline (usually a small reduction).

When a vehicle goes uphill, similar forces are involved, but the signs associated with these forces change. Figure 57 shows the forces for this situation. In this case, the force due to weight along the incline helps to decelerate the vehicle:

$$- mg \sin\theta - \mu mg \cos\theta = ma$$

where θ is the upward inclination angle. Dividing through by the mass m shows that there are two deceleration forces: one due to the component of weight along the incline and one due to the normal force along the incline (which is reduced in magnitude by cos θ).

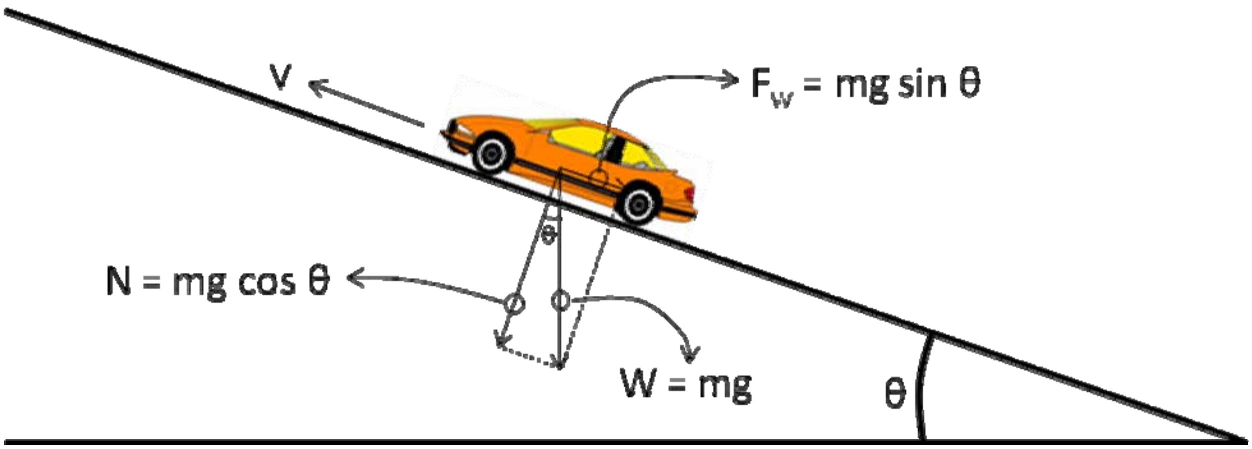

Figure 57. Forces on a Vehicle created by an Uphill Slope

To obtain an idea of the effects of inclines on stopping distances and stopping times, typical values can be substituted for the various quantities. Table 7 shows these quantities for a 3 deg slope, in comparison with a level road, and Table 8 shows these quantities for a 6 deg slope. Almost all slopes of highways are less than 6 deg, so that the range of effects is essentially covered in the two tables. Only very hilly terrain would not be covered by the tables, and of course, could be calculated if necessary. In the tables, μ is assumed to have a value of 0.6. This would represent rather severe braking, which of course, a driver would use to avoid a rear-end crash if he or she were aware of the circumstances.

Table 7. Braking Times and Braking Distances for 3 Deg Downhill, Flat, and 3 Deg Uphill Roads (μ = 0.6)

	Downhill, 3°		Flat		Uphill, 3°	
Initial Speed (mph)	Braking Time (s)	Braking Distance (ft)	Braking Time (s)	Braking Distance (ft)	Braking Time (s)	Braking Distance (ft)
30	2.50	55.0	2.28	50.1	2.10	46.1
45	3.75	123.7	3.42	112.7	3.15	103.8
60	5.00	219.9	4.46	200.4	4.20	184.6

Table 8. Braking Times and Braking Distances for 6 deg Downhill, Flat, and 6 deg Uphill Roads (μ = 0.6)

Initial Speed (mph)	Downhill, 6°		Flat		Uphill, 6°	
	Braking Time (s)	Braking Distance (ft)	Braking Time (s)	Braking Distance (ft)	Braking Time (s)	Braking Distance (ft)
30	2.78	61.1	2.28	50.1	1.95	42.9
45	4.16	137.4	3.42	112.7	2.92	96.5
60	5.55	244.3	4.555	200.4	3.90	171.5

The tables show clearly that stopping times and stopping distances are increased when going downhill and are decreased when going uphill. This means that in downhill situations, more distance will be needed between vehicles to avoid rear-end crashes, and similarly, in uphill situations less distance between vehicles is needed. These results suggest that if all other aspects are the same, the enhanced rear lighting should be triggered earlier on downhill slopes and possibly later on uphill slopes.

Next, consider the output of a strapped-down accelerometer in the lead (equipped) vehicle. This accelerometer would read the acceleration and deceleration along the longitudinal axis of the vehicle. When the vehicle is on an incline, a gravity component will be present in the output. (In this analysis, pitch change of the vehicle resulting from braking will be neglected. This pitch change will be present on flat ground as well as on slopes, so that neglecting the component will have little effect.)

Figures 58 and 59 depict the situation. The gravity component will add a deceleration component to the deceleration component due to braking on a downhill slope (Figure 58), resulting in a higher reading of deceleration coming from the accelerometer. This can best be visualized by considering the accelerometer to be made up of a mass with a centering spring. The vehicle on the downhill incline will cause the mass to move forward due to gravity and also due to braking. Consequently the two components add to produce a higher reading of deceleration. In Figure 59, the uphill situation, the accelerometer produces a reduced reading because the gravity component subtracts from the braking deceleration component. These results indicate that on a downhill incline, an accelerometer will be biased upward in deceleration magnitude and will reach threshold more quickly. Similarly, the results indicate that on an uphill incline, an accelerometer produces a lower reading of deceleration. Therefore, on an uphill incline, an accelerometer is biased downward in deceleration magnitude and will reach threshold more slowly. Examples are shown in Table 9 for 3 and 6 deg slopes. As can be seen, the biases are important.

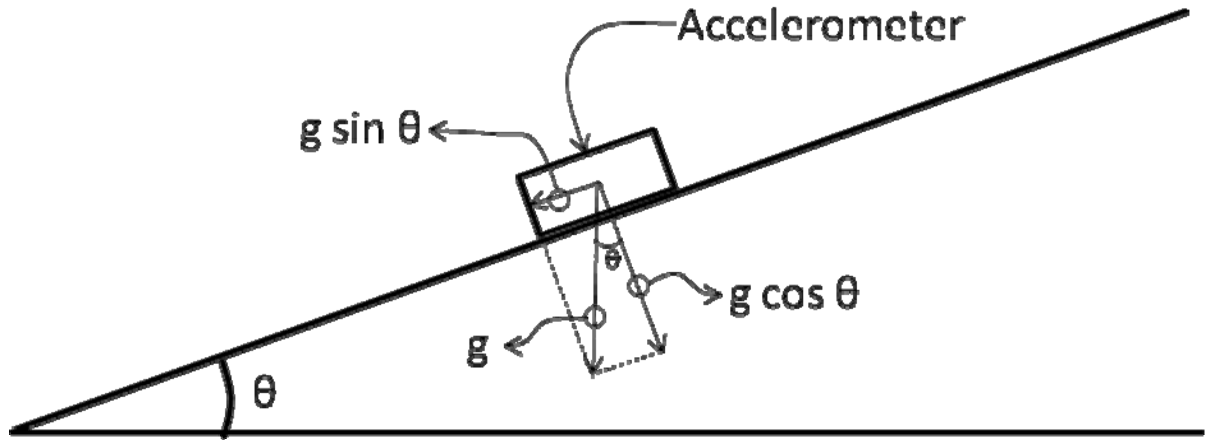

Figure 58. Effects of a Downhill Slope on a Strapped-Down Accelerometer

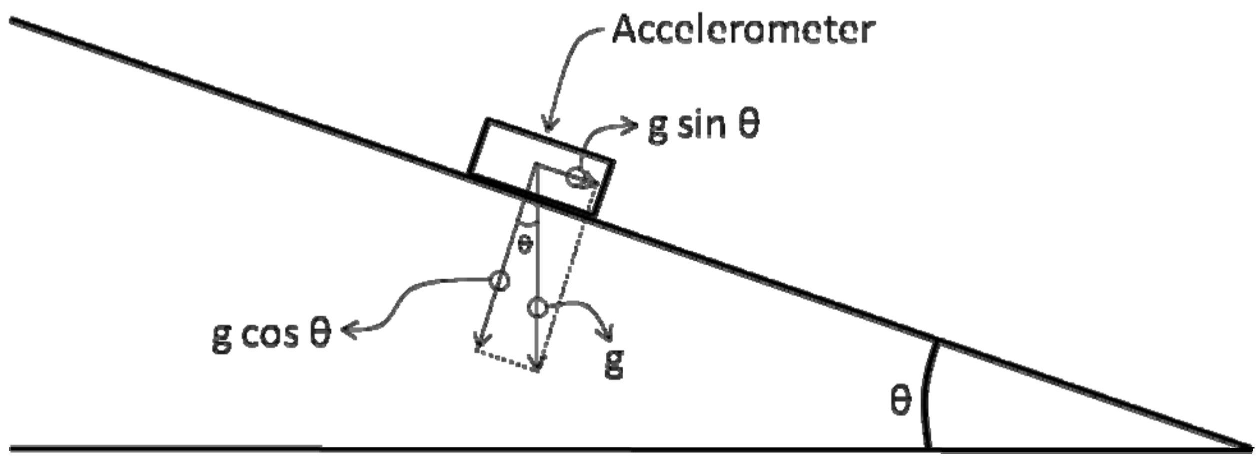

Figure 59. Effects of an Uphill Slope on a Strapped-Down Accelerometer

Table 9. Deceleration Magnitude Bias as a Function of Incline

Downhill, 6°	Downhill, 3°	Flat	Uphill, 3°	Uphill, 6°
0.105g high	0.052g high	0	0.052g low	0.105g low

Suggested Approach to Uphill-Downhill Problem

These analyses indicate that if a given accelerometer threshold is maintained when the lead vehicle is on an incline; the enhanced rear lighting will be activated somewhat earlier on a downhill incline and somewhat later on an uphill incline. This situation can compensate for changes in stopping distances and times. On downhill inclines, stopping distances and times are increased and on uphill inclines, stopping distances and times are decreased. Therefore, on a downhill incline a following driver should be warned sooner, and on an uphill incline a following driver could be warned slightly later. It appears therefore that the solution is to not change the specified threshold, because the accelerometer will be biased in an advantageous direction.

A counter-argument would be that the lead driver and following driver may not behave similarly in terms of decelerating to a stop. Accordingly, an analysis should be carried out to determine whether or not retaining the original threshold is the best strategy. However, such an analysis would require many assumptions and might result in a much more complicated system, including gyro-stabilization and introduction of GPS (global positioning system) and map-matching inputs. It would seem that such complications should be left to second generation systems, if used at all.

Decelerating/Turning Vehicle Problem

This problem occurs when a lead vehicle undergoes sufficient deceleration to trigger the enhanced rear lighting, but then turns a sharp corner. The problem arises at intersections because after the turn the lead vehicle may be followed by a different driver. The new driver could be confused by the enhanced rear lighting, particularly the time-out portion. The desired solution would be to extinguish the enhanced rear lighting when the lead vehicle has turned the corner. This would likely reduce confusion for the new following driver.

In this situation, once the lead vehicle has cleared the intersection (by turning), it is no longer a threat (in regard to a possible rear-end collision) to the original following vehicle. Therefore, there is no need to continue the enhanced rear lighting signal.

There appear to be two strategies for extinguishing the rear lighting. Both involve an override system that extinguishes the rear lighting, regardless of the state of other elements in the system. The first of these involves use of a steering threshold and the other involves use of an accelerator threshold. For the first strategy, it is usually the case that drivers do not use large steer angles unless they intend to turn. Therefore, by placing thresholds on the magnitude of the steering input, it should be possible to determine when the driver is performing an intended turn. Once a threshold is exceeded in either direction of turn, an overriding timeout of perhaps 10 s could be used to extinguish the rear lighting.

The steer-angle approach has two problems: first, it might extinguish the lighting while the lead vehicle is still in the intersection, either wholly or partly; and second, the lead vehicle driver might try to steer around an obstacle or other vehicle. In either case, it would be desirable for the enhanced rear lighting to remain activated.

Another approach is to take a signal from the accelerator. It is extremely unlikely that a lead vehicle driver would step on the accelerator while involved in heavy braking. In addition, the probability is very high that in a relatively sharp turn the driver would not accelerate until the turn is completed, or nearly so. Therefore, it appears that it would be safer to extinguish the enhanced rear lighting *after* the driver begins to accelerate. A simple binary signal would be sufficient if it indicated depression/no depression of the accelerator. Upon depression, the enhanced rear lighting signal could be extinguished.

The accelerator depression signal must be used with caution. An overriding time out approach would not be acceptable. Rather, an instantaneous approach must be used. The reason for use of an instantaneous approach is as follows:

In normal driving, braking emergencies develop very quickly, and usually involve removing the foot from the accelerator and placing it on the brake pedal. A high deceleration signal is then likely to follow. Since deceleration is the signal used for activating open-loop systems, nothing should override this signal unless there is reasonable certainty that the lead vehicle is no longer a threat.

While there may be instances where the driver, after making a turn, accelerates but then lifts the foot, these instances are not as serious as extinguishing the enhanced rear lighting too soon due to time out.

Suggested Approach Decelerating/Turning Vehicle Problem

The approach to overcoming the nuisance problem caused by timeout in turning situations is to use a binary accelerator signal. Whenever, the accelerator is depressed, the rear lighting is instantaneously deactivated. This approach should solve the turning vehicle problem, but should not otherwise affect the needed enhanced lighting.

Accelerometer Noise Problem

As indicated, the strapped-down accelerometer used to trigger the enhanced rear lighting operates in a noisy environment. This noise can be attributed to vehicle vibration that results from the engine and other running gear as well as roadway roughness. An extreme example of this is driving over a pothole. Under such a condition, spikes of deceleration are likely to appear in the accelerometer output. If care is not taken, such decelerations might trigger the enhanced rear lighting system. The easiest way to prevent this problem from occurring is to use a low pass filter at the output the accelerometer. This filter may be analog or digital, depending on the system design.

There is a tradeoff in the design that must be taken into consideration. On the one hand, the peaks must be smoothed sufficiently so that they don't cause the enhanced rear lighting system to trigger. On the other hand, if the smoothing is too heavy, it will slow the response of the accelerometer in detecting that the trigger threshold has been exceeded. Since prompt warning of the following driver is essential, great care must be taken in designing the filter.

If it is assumed that a second-order continuous low-pass filter is to be used, the equation of the filter in transform becomes

$$\frac{E_o(S)}{E_i(S)} = \frac{1}{1 + 2\frac{\varsigma}{\omega_n}S + \frac{S^2}{\omega_n^2}}$$

where $E_o(S)$ is the transform of the output of the filter, $E_i(S)$ is the transform of the input to the filter, S is the Laplace transform variable, ω_n is the natural frequency in radians per s, and ς is the damping coefficient. The design problem becomes one of selecting ω_n and ς, so that the filter has the "correct" response. The damping coefficient, ς, can be selected so that there is no appreciable overshoot to a step input. This means that a step change in response will be smoothed, but at the same time the response is reasonably fast. A value of 0.8 will result in an overshoot of 1.5 percent, which would be acceptable. To specify ω_n it becomes necessary to specify the rise time of the filter to a step input. For a damping of 0.8, the 90percent rise time is given by the equation

$$\omega_n t_r = 2.8, \quad \text{where } t_r \text{ is the zero-to-90\% rise time in s.}$$

Assuming that such a rise time should be 0.1 s, the value of ω_n can be calculated: 28 rad/s. This corresponds to 4.5 Hz. This type of filter can be synthesized using three operational amplifiers and should perform well as a smoothing filter. At the same time, delays caused by the smoothing should be minimal.

This example shows that accelerometer noise reduction can be handled by an appropriately designed low pass filter. The example shows how this could be accomplished using standard analog techniques. The problem could also be handled using a digital approach. It is important to stress that while there are good solutions to accelerometer noise reduction, the problem must not be overlooked. If neglected, false triggering will no doubt occur.

Triggering Using ABS

It has been suggested that ABS should be used as the method of triggering the enhanced rear lighting. This suggestion has merit, but it also has problems. All previous research at VTTI indicates that the triggering threshold should be between 0.35 and 0.40 g of deceleration. This should be followed by timeout of approximately 5 s, once deceleration has dropped below 0.15 g. The triggering criteria previously developed at VTTI are based on experimentation and on examination of the 100-Car data. The two approaches are in agreement in terms of results.

ABS is used to stabilize a vehicle in very hard braking or when one or more individual wheels lose adhesion, such as on slick roads. ABS is only activated when the brake pedal is depressed and only under the conditions stated, that is, very heavy braking or loss of adhesion. The difficulty with using ABS exclusively is that it may miss many important cases where enhanced rear lighting would be desirable and helpful in preventing or reducing the severity of rear-end collisions. It is estimated that, in general braking on dry hard-surfaced roads, decelerations at or above 0.7 g of would be required to activate ABS. In particular, at least one of the wheels must be skidding over the pavement. This level of deceleration is well above the 0.35 to 0.40 g level called for in the VTTI approach. It is clear that if ABS alone is used, there will be many cases where the enhanced rear lighting would not be triggered, but if used, would be helpful in preventing rear-end crashes. Thus, the VTTI criteria would cover many more situations.

There is nevertheless one important case where ABS may be helpful as an adjunct. It is possible that when conditions for adhesion have deteriorated and the equipped vehicle has not reached a deceleration of 0.35 to 0.40 g, it would indeed be desirable to trigger the enhanced rear lighting. This would alert the following driver to an emergency ahead. Deteriorated conditions can occur when there is ice or snow on the road, or possibly when there is slickness due to rain or gravel on top of the pavement. When such a condition occurs, ABS is usually activated for a relatively short period of time, perhaps 1 to 1.5 s. Consequently, it would appear desirable to extend the enhanced rear lighting by means of timeout, as is done with the VTTI-proposed criteria.

Recommended Approach to Triggering

Figure 60 shows a block diagram of the overall triggering system including ABS and accelerometer derived criteria. This is the configuration recommended for field tests. It includes an accelerator depression signal for turning vehicles. The block diagram summarizes the considerations discussed in this chapter.

In operation, it is expected that the main method of triggering would be by means of the strapped down accelerometer. The filtered output would be subjected to a Schmidt trigger that would go high when the deceleration reached 0.4 g. It would remain high until the deceleration decreased to 0.15 g, at which time a 5 s timeout system would become active. On downhill inclines, the accelerometer output would be biased upward as described. This would mean that triggering would occur slightly earlier. Similarly, on uphill inclines, triggering would occur slightly later.

The triggering system would include ABS activation similarly followed by a 5 s timeout. If ABS is activated even though the 0.4 g deceleration criterion is not reached, the enhanced rear lighting would still be activated.

If the driver of the equipped vehicle should use the accelerator, the lighting would be instantaneously suppressed. As explained, this would cause the lighting to be suppressed on sharp turns, where the driver begins accelerating. There is no timeout associated with the accelerator depression signal because of the possibility of a rapid movement from the accelerator to the brake pedal and heavy braking, which would appropriately trigger the enhanced rear lighting.

It is expected that some fine tuning of the triggering system may be necessary. However, considering the amount of previous experience that has already been gained in regard to triggering, large changes should not be necessary.

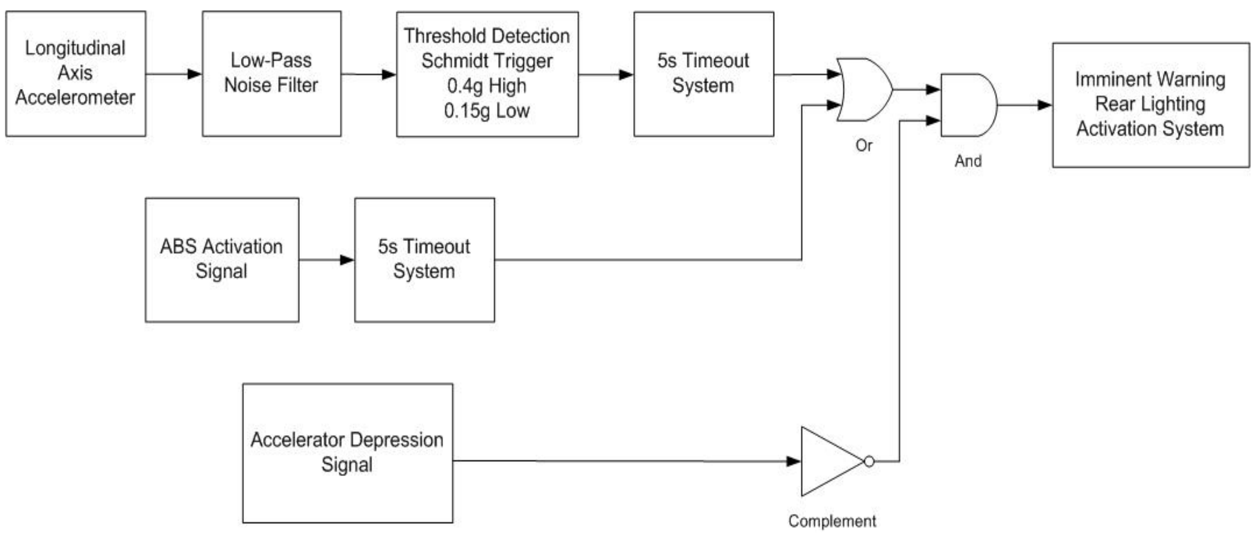

Figure 60. Block Diagram of the Triggering Logic for the Enhanced Rear Lighting

Chapter 6. Summary and Conclusions

General Findings

Perhaps the most important finding of the Phase 1 research is that rear lighting continues to look promising as a means of reducing the number and severity of rear-end crashes. Based on all data available, it appears that both human behavior occurring in rear-end crashes and the technology available can be matched to help solve the problem. Considering how many of these crashes there are and how costly they are, indications suggest that appropriate rear lighting may have a substantial role to play in reducing the number of these crashes as well as the severity of those that do occur. Specific findings from the research are provided in this chapter.

LED Optimization

- Individual LEDs, if used in sufficient quantity and having present-day output brightness, are capable of competing and even exceeding incandescent lamps in terms of effectiveness. This finding indicates that as manufacturers continue to move to LED lamps for rear lighting, enhanced signals can also be developed using the same technology.
- Beam widths with LED lamps will need to be narrower than with incandescent lamps. However, since with few exceptions it is the vehicle directly behind that creates the hazard associated with a rear-end crash; a narrow beam width does not present a limitation. In fact it is an advantage in that drivers in adjacent lanes do not have to incur the nuisance of bright rear lighting. While there will be light in the adjacent lanes, it will be substantially attenuated.
- Closely associated with the narrower beam width of LED lamps is the finding that rated discomfort glare is lower in adjacent lanes than that of incandescent lamps (which have wider beam widths). To achieve necessary brightness levels using LEDs, beam widths must be relatively narrow. This allows concentration of the light where it is needed, that is, directly behind the equipped vehicle.
- Optimum flashing frequencies are slightly higher for LED rear lighting than for incandescent lighting. This phenomenon is a result of the much faster activation and extinguishing times of LEDs. Whereas incandescents may have rise times of 50 ms, LEDs may have rise times of 2 ms. Similarly, extinguishing times for incandescents may be 150 ms while LEDs may be 4 ms. To the observer, LEDs appear to light and extinguish instantaneously, but incandescents take a short time to light and extinguish. As frequency is increased with incandescents, a tradeoff occurs between having distinct pulses of light and the ability to observe the optimum frequency (which is somewhat higher). On the other hand, with LEDs there is no such tradeoff. Optimum median frequencies were found to range between 4.75 and 6.0 Hz for LEDs. Earlier results for incandescents indicated an optimum frequency of 4.0 Hz.

Static Testing

- Flashing improves rated attention-getting with LED rear lighting. This result is similar to previous results for incandescent lighting.
- The LED TCL was not among the best finalists for rated attention-getting. This result could be attributed to the TCL's compact size. In addition a much simpler flashing CHMSL could be substituted for the TCL.
- Optimum configurations suggest that size and expanse of the output across the outer rear of the equipped vehicle improves attention-getting. The best configurations in terms of rated attention-getting were the following:

  1. Outboard lamps simultaneously flashing, CHMSL alternately flashing at 4.75 Hz, and
  2. All lights simultaneously flashing at 5.0 Hz.

  Both of these took advantage of flashing the outboard lamps, which was believed to be an important cue.
- Rated discomfort glare is closely related to rated attention-getting. It appears that it is necessary to accept somewhat greater rated discomfort glare to achieve greater attention-getting.
- The later static outdoor tests showed substantial eye-drawing capability for the better-rated rear lighting under surprise conditions. During the first exposure, participants looked up to the rear lighting display 56 percent of the time while glancing to a navigation display under light visual and cognitive load when all lamps flashed simultaneously at the 5.0 Hz rate and with enhanced rear lighting brightness.
- The same tests showed that normal rear (brake level) lighting activation produced *no* eye-drawing capability and also that simply flashing at this lighting level produced only 19percent look up. Thus, lighting level is very important, with added brightness greatly improving the eye-drawing capability.
- The incandescent TCL had lower eye-drawing capability than the simultaneous flashing of all LED lamps with increased brightness. This result allows direct comparison with the earlier experiments performed at VTTI.
- Later ratings of attention-getting and discomfort glare were similar to earlier findings. However, the incandescent TCL stood out as having a higher level of discomfort glare in relation to its attention-getting.
- The use of simultaneous flashing with increased brightness received a mean discomfort glare rating near 5, which corresponds to "Just acceptable…I might want to look away in less than a minute." This level of discomfort glare would be considered acceptable, because it is unlikely that drivers would ever be exposed for more than 6 s.

Roadway Evaluation

- The on-road experiment met with moderate success in terms of gathering appropriate data. In particular, very few events occurred in which eye-drawing capability could be measured. Nevertheless, data were obtained for determining driver behavior, whether looking away or not.
- In terms of eye-drawing, the sparse available data do suggest that flashing with increased brightness may be effective in reducing the incidence of long off-road glances.
- Drivers exposed to the flashing with increased brightness were more likely to brake in response as compared with conventional, steady brake level signals. This suggests that flashing with increased brightness represents a strong cue, relatively speaking.
- Despite attempts to quantify signal annoyance, drivers did not appear more likely to pass or change lanes. Those exposed to the flashing with increased brightness signal tended to decelerate. This was attributed to caution on their part.

Triggering Criteria

- In regard to the open-loop triggering analysis, it appears that uphill and downhill situations more or less take care of themselves in terms of triggering. The goal appears to be to trigger later in uphill situations and earlier in downhill situations as a result of differences in stopping distances. However, a strapped-down accelerometer would do exactly that in regard to a fixed threshold, so no change is needed. While more precise analyses are possible, the assumptions that must be made would be quite tenuous and complexity would increase dramatically.
- It would be important to use an appropriate low pass filter on the accelerometer so that triggering does not occur over bumps or other forms of shock and vibrations. This filter could be implemented using either analog or digital technology.
- An ABS (antilock braking system) signal can be included as a useful adjunct to triggering. This signal would become effective when the deceleration threshold has not been reached, but one or more of the wheels have lost adhesion. A timeout interval should also be used, because ABS is usually activated for a very short period of time, on the order of 1 s. The enhanced rear lighting would then serve as a warning to the following driver, who would then recognize, hopefully, that something was amiss with the vehicle ahead.
- Drivers performing sharp turns in an equipped vehicle after decelerating would usually step on the accelerator after completing the turn. To avoid confusion, the accelerator logic signal could be used to instantaneously extinguish the enhanced rear lighting.

- It is possible to develop a triggering system that accounts for all of the cases mentioned. This system is relatively simple and is recommended for use in deployment.

Phase 1. General Conclusions

The principal conclusion that should be drawn from the Phase 1 research is that enhanced rear lighting signals remain promising as a method for reducing the number and severity of rear-end crashes. To be effective, the signal should have the following characteristics:

- The signal should have increased brightness, should flash all lamps at 5.0 Hz, and should be highly directional (aimed directly backwards).
- (If open-loop systems are used) use of the triggering system proposed in Chapter 5 is recommended. This system accepts signals from a strapped-down accelerometer and from the ABS as well as from the accelerator. In addition, it filters the output of the accelerometer so that shock and vibration do not cause inadvertent rear lighting activations.
- LED technology is the preferred technology for implementation of the signal because of its sharp rise and fall times and because automotive lighting is likely to continue to move toward LEDs for rear lighting.

Another important conclusion is that work should continue with enhanced rear lighting because of its promise. Particular aspects that should be examined are as follows:

- The LEDs used in the lighting units should be more carefully examined with the goal of developing arrays that would better fit present-day light vehicles. All previous work has been with the round units. However, there is really no need for the units to be round. If an appropriate base material is obtained, the LEDs could be imbedded and wired appropriately to serve as a more uniform array fitting the specific light vehicle.

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APPENDICES

Appendix A.

Summary of Stakeholder Virtual Workshops

VTTI convened a series of stakeholder workshops with representatives from industry and related disciplines and areas (e.g., automotive manufacturers, suppliers, safety experts, and government regulators) in order to provide the opportunity for individuals to share their experience regarding rear signaling system concepts or designs, as well as provide valuable insights on previous project work and future directions. The virtual workshop was designed to foster discussion and gather information on key issues, including:

- Candidate system functions and operational concepts for enhanced braking lighting;
  - Hard braking, stopped vehicle, integration with other functions and features (existing lamps, brake assist, etc.);
  - Discuss previous or current work in this area;
- Explore the feasibility of rear brake light concepts;
  - Identify important criteria and constraints (costs, power, styling) for determining what is or what is not feasible;
  - Assess the extent to which proposed concepts and systems need to stay within the existing framework of current or proposed production brake lamps;
- Need for standardization of signals;
  - Expected effects of using non-standardized signals (several systems);
  - Aspects, dimensions, or characteristics believed to be important to standardize or define limits;
- Metrics and methods for evaluating enhanced rear brake light systems.

Approach

Unlike traditional meetings, this workshop was convened as a virtual meeting using a variety of alternative formats, including remote teleconferencing with individual stakeholders, web-based meetings, and face-to-face discussions. Thus, rather than a single meeting, there were actually a series of smaller stakeholder meetings. One key benefit of this approach is that it allows discussions to take place under the umbrella of anonymity - this can set the stage for franker and open communications. Meetings were also conveniently arranged to accommodate participant schedules without the need to coordinate large numbers or groups of individuals. Furthermore, although discussions focused on a set of basic, common underlying issues (outlined above), no standardized set of questions were necessarily developed. Beyond the basic issues, questions were tailored to address the background of the individual participants. VTTI assembled a PowerPoint presentation that addressed each of the above topic areas; this presentation was used to guide the discussions.

Participants

Representatives from each of the following organizations participated in the virtual workshop interviews: BMW, Ford/Volvo, General Motors, Honda, Mercedes-Benz, Nissan, Toyota, and Westat.

Findings

The following summarizes key discussions and topic areas covered during the workshop. Individual summaries with specific stakeholder groups are included in the sections that follow.

1. Any new signals should attempt to conform to (take advantage of) the existing brake lamp frameworks/housings.
2. Standardize relevant (performance-related) functional system characteristics as much as possible. Triggering criteria, in particular, should be standardized.
3. System evaluations must also measure unintended consequences associated with the introduction of any new signals. It is not sufficient to merely measure performance benefits – also need to ensure signals are not introducing disbenefits.
4. Evaluations should include a control or comparison condition using a type of Forward Collision Warning (e.g., audible alert). This will help to understand the relative benefits of the various approaches. Assessments should also include closed-loop concepts, particularly for stopped lead signals.
5. Both incandescent and LED configurations should be examined. However, standards should be based on functional system characteristics and not technology.

What Makes for an Effective Signal?

- The signal must capture (and/or redirect) the attention of a distracted driver.
- An effective signal must also reduce or minimize unintended consequences.
- Must be intuitive and quickly understood by drivers.
- Must be novel (effectiveness should be maintained over time).
- A signal that addresses the stop lead vehicle problem (which represents a big part of the rear-end crash problem) would be a great enhancement.
- Approach should not rely on discrete changes (e.g., change in brightness, number lamps, color, etc.) which may not be readily perceived (i.e., driver looking away at the time of the change).

Candidate Concepts, Design Recommendations, and Recommended Research

- Staged approaches wherein the level of deceleration is communicated in some manner are not generally recommended.
    - Can add complexity and visual noise.
    - May fail to capture the attention of a distracted driver. Signals that rely on discrete changes may not be perceived.
    - Misses the point; driver's are very good at judging closing rate <u>when looking forward</u>. Drivers are good at estimating time-to-collision (and the need to brake

hard) when they are looking forward even with short 1-sec glances to the vehicle ahead. Thus, an effective signal would capture and redirect the driver's attention to the forward roadway and not necessarily attempt to code level of deceleration.

- Use the CHMSL to communicate deceleration signals
- Flash existing outboard brake lamps. May not need sustained or continuous flashing; a short series of flashes may be sufficient to capture the driver's attention. An option would be to initially flash the CHMSL to gain driver's attention followed by increase of outboard lights to make use of looming (similar to Federal Highway Research Institute's recommendation).
- Design system to allow more warning time (e.g., pre-charge system based on quick accelerator pedal release)
- Systems that use looming cues may be more effective at night compared to daytime.
- Several strategies are possible following a hard deceleration event: transition to a different signal (new cue) to indicate a stop, or continue with hard deceleration signal (e.g., flashing lights).
    - Need to determine how long the "stop" signal should remain active.
    - Could also introduce a delay (e.g., wait 2-3 sec before activating signal after the vehicle comes to a complete stop).
- Closed-loop approaches are most relevant for the stopped lead vehicle application. If a stopped lead signal is used, it should be part of an active, closed-loop system (e.g., signal activates only if there is an approach vehicle in the lane, signal turns off when the following vehicle is stopped, etc.). An inexpensive narrow beam sensor could be used to detect the presence of an approaching vehicle.
- Deceleration should not be the only triggering criterion. Deceleration threshold may also be adjusted for speed.
- Narrowing the width or focus of the visual signal may help to reduce annoyance and unintended consequences from adjacent traffic
- Explore unintended consequences as part of the research paradigm.
- Examine effectiveness of signals under varying environments (day/night, low visibility, etc.)

<u>Current Concepts Being Considered</u>

- Mercedes-Benz, Adaptive Brake Light
    - All three brake lamps flash (frequency 5 +/- 2 Hz) during emergency braking maneuver, hazards flash when vehicle stops following emergency braking
    - Triggers when vehicle speed > 31 mph AND at least one of the following:
        - Deceleration > 7m/s2 (0.7 g) and/or
        - Brake assist function active and/or
        - Electronic Stability Program detects a panic braking operation
- Volvo, Emergency Brake Lamp
    - "Warns other drivers of your emergency brake status. When the car's deceleration exceeds 0.7g, or when antilock brakes are activated, the brake lights are accentuated by becoming brighter."

- BMW, Brake Force Display
  - "Enlarges the surface area of the brake lights as you increase the rate of braking" (BMW 7-Series, 5-Series, 6-Series, X3)
  - Activates at 0.5g deceleration
- Peugeot
  - Automatic Illumination of Hazard Lights by Sharp Deceleration
  - Peugeot 607

Feasibility: Implementation Factors & Considerations

- Cost, power and styling are always considerations in the design of a system. It would be preferable to take advantage of and use the existing vehicle's lighting frameworks/housings.
  - Flashing lamps, for example would be more preferable than the requirement to enlarge the surface area. Flashing brake lamps is a simpler mechanization than the others signal approaches discussed that can be more difficult to implement.
  - Increasing the brightness of the lamps has the potential to overload the LED's to the point of failure.
- Flashing LED's may leave a ghost image
- The number of electrical drivers (e.g., lights) is one of the limiting factors (e.g., a light bar with 8 lamps would be much more complicated to implement).
- If flashing is used as a signal, ensure that the flash rate is not inducing epileptic seizures in the population; suggest staying under 5 Hz flash rate.

Standardization

- From a Human Factors perspective, it would be desirable to standardize systems, since it would increase consistency and enhance driver performance. Need to avoid having different solutions or implementations across vehicle platforms.
- The focus for standardization should relate to relevant performance or functional characteristics of the system and not technology-based elements (e.g., LED versus incandescent bulbs). Essentially, performance-related aspects should be standardized, but no component that affects styling. The following key characteristics should be considered for standardization:
  - activation speed,
  - deceleration trigger,
  - warning strategy or approach,
  - the type of cue used to signal hard deceleration events
  - the rate of flashing
  - location of brake lamps, etc.
  - how long the signal will be active following an event (de-activation criteria)
- Standardization criteria should allow for future technologies.

Evaluation Metrics/Scenarios

- Participants generally agree that eye-drawing power of the signal is an important characteristic that should be used to evaluate potential effectiveness. May also need to increase the salience of cues when drivers are looking forward (onset of a different cue to signal hard braking).
- Define and measure potential unintended consequences, including the extent to which signals (e.g., startle attentive drivers, distract drivers in adjacent lanes, annoy drivers, driver's ability to differentiate these signals from other common signals, lower response to conventional brake signals, etc). Capturing and measuring unintended consequences can be much more difficult than characterizing performance benefits.
    - One approach could be to instrument a small community or concentrated area with the brake signals and assess the effects over time. This may allow unintended consequences to be more readily discernable by polling drivers in the community. Also consider using bumper stickers on host vehicle to gather comments from surrounding traffic.
- CAMP research suggests that you can't differentiate between hard braking and panic braking on the basis of brake pedal travel and brake pedal rate of travel.
- Evaluation scenarios should include:
    - Situations where the turn signal indicator is activated – assess whether the brake signal is equally effective compared to the no turn indicator condition.
    - Vehicles in adjacent lanes at the time of lead vehicle braking (signal activation). Assess whether the signal distracts or otherwise alters the performance of the drivers in the adjacent lanes.
    - A scenario that focuses on the transition in signals (if any) between hard deceleration and a stop.
- Testing can be performed on public roads using methods suitable for public roads – activate the brake signal manually without pairing it with actual lead vehicle hard decelerations. Allows you to capture the eye-drawing power of the brake signal without the risk of hard braking events.
- Compare Forward Collision Warning to Rear Signaling Implementations. Also suggested to benchmark with an auditory condition.

Other Items and Notes

- Do existing regulations allow flashing hazards for use as a stopped lead signal?
- For the Pilot or FOT, consider recruiting 100-Car drivers (the ones with a history of poor driving performance).
- Consider using fleets for operational tests (e.g., taxicabs, mail carriers, etc).
- The idea of passively using the brake lamps to signal hard deceleration or a stopped lead vehicle may be a short-lived or limited concept in light of other advances in the collision avoidance arena. Movement towards more sophisticated active warning and avoidance systems (vehicle to vehicle communications, collision warning, automatic braking, etc.) may make this concept obsolete and of little relative benefit. Need to consider whether this line of research is worthy of continuation, or how it can be combined with more active features (closed-loop systems).

Appendix B.

Counterbalancing Schemes Used in the Frequency Optimization/TCL Pattern Selection Experiment and in the Attention-Getting/Discomfort Glare Experiment (Chapter 2)

Frequency Optimization/TCL Pattern Selection Experiment

There were five flashing conditions for which the frequency had to be optimized. These are labeled 1 through 5 below. Participants also had to rank order the TCL patterns. This task is labeled T below. The experiment thus had six conditions, and it used twelve participants with the orders given below. Note that for each order there was an exact reverse order. In regard to gender distribution among participants, the forward and reverse orders used the same gender.

S1m:	1	2	3	4	5	T
S2f:	T	1	2	3	4	5
S3m:	5	T	1	2	3	4
S4f:	4	5	T	1	2	3
S5m:	3	4	5	T	1	2
S6f:	2	3	4	5	T	1
S7m:	T	5	4	3	2	1
S8f:	1	T	5	4	3	2
S9m:	2	1	T	5	4	3
S10f:	3	2	1	T	5	4
S11m:	4	3	2	1	T	5
S12f:	5	4	3	2	1	T

Attention-Getting/Discomfort Glare

Once the frequencies for the five flashing conditions and the pattern for the TCL had been selected, the attention-getting and discomfort glare ratings were obtained. However, there was a complication in that the "steady on" condition had to be rated. As mentioned, it had been decided to determine the "overall" best frequency for each flashing configuration and the optimum pattern for the TCL. These were used in the attention-getting/discomfort glare experiment by all participants. This required using a new group of participants, because 14 would be required to obtain a reasonable counterbalance. These were all fresh subjects, that is, subjects who did not participate in the frequency optimization and pattern selection experiment; thus eliminating the need to control transfer effects between the two experiments. The steady condition is designated by an S in the counterbalance scheme shown below:

S1m:	S	1	2	3	4	5	T
S2f	T	S	1	2	3	4	5
S3m	5	T	S	1	2	3	4
S4f	4	5	T	S	1	2	3
S5m	3	4	5	T	S	1	2
S6f	2	3	4	5	T	S	1
S7m	1	2	3	4	5	T	S
S8m	T	5	4	3	2	1	S
S9f	S	T	5	4	3	2	1
S10f	1	S	T	5	4	3	2
S11m	2	1	S	T	5	4	3
S12f	3	2	1	S	T	5	4
S13m	4	3	2	1	S	T	5
S14f	5	4	3	2	1	S	T

Note that distribution of males and females was handled in the same way as the Frequency Optimization/TCL Pattern Selection experiment, except for participants 7 and 9. Here the order pair (forward/reverse) was split to keep the total number of males and females in the experiment equal.

Appendix C.

Instructions Associated With Chapter 3 Involving Additional Static Evaluations

Effective Intensity Rating Scale

Ranks

[position the vehicle in its original location, 100 ft from the vehicle appliqué mockup in the same lane]

We will show you three patterns, and we would like you to rank them in order of their effective intensity. Effective intensity relates to your subjective impression or perception of how bright the lights are – regardless of the pattern (arrangement of the lamps, or whether they are flashing or constantly on).

1) First we will run through each of the patterns
2) Now we'll run through them again. This time tell me if you think there's a difference among them in terms of their effective intensity, OR if you believe they are all the same (circle one)

   SAME DIFFERENT

[Note: this is intended to see if participants believe any of the LED versions are different from each other given same brightness, but different patterns].

IF DIFFERENT

3) OK, this time tell me which pattern you believe has the highest effective intensity (Mark as #1)
4) Now we'll run through them again. This time tell me which you believe has the least effective intensity (Mark as #3)

____ Optimized Simultaneous Flash, Increased Brightness
____ Increased Lamp Intensity
____ Outboard Simultaneously Flashing, CHMSL Alternately Flash

Instructions for Surprise Event: Navigation System Interactions

Set-Up

- Participant is seated in the driver's seat (seating position adjusted)
- Vehicle engine on
- Navigation screen is up and set to main display (map view)
- DAS system on and actively collecting data

Instructions

- As you can see, this car is equipped with an in-vehicle navigation system; this is the main display screen <point to screen>. And these are the associated controls for operating the device <point to controls>.
- These systems are intended to guide you to a destination, but before they can do that, they must be programmed.
- We're interested in getting your opinion about the relative ease associated with programming a destination.

(DEMO: First Trigger)

- I will be demonstrating some simple steps for selecting a destination, and then you will have an opportunity to try it out. Any questions before we start?
- OK, I'm going to use the City feature to program the system to direct us to Pulaski, VA. Here are the steps:

    1) First, Press the **Destination** button
    2) Then, scroll over to highlight the "**City**" button and select it (you scroll by using this joystick, then press down on the joystick to select)
    3) Then **type in Pulaski** using the joystick to highlight and select the characters on the screen
        a. **[TRIGGER 1: When Highlighting/Entering a Letter]**
    4) Once you've finished typing, scroll to and select the "**List**" option
    5) Then select the "**Enter**" option (this should already be highlighted)
    6) Then select "**OK**" under the destination settings menu (should already be highlighted)
    7) Finally, select "**Yes**" for the time option and restricted roads.
    8) The program will then be plotted and displayed on the map.

(DRIVER TASK)

- Do you have any questions?
- OK. Now I'd like you to try it by programming a rout to ROANOKE. I'll help you along the way.
- Okay, go ahead and press the **Destination button** to bring up the main destination entry menu
- Now, scroll over and select the "City" menu option
    - o **[TRIGGER 2: As They Scroll to City Option]**

- Now use the joystick to type in ROANOKE (remember to highlight the character, then select by depressing the joystick).
    - **[TRIGGER 3: As They Enter ROANOKE]**
    - Once lights are triggered, (don't look up yourself)
    - Wait to administer the de-brief until the driver completely finishes the destination entry task

(DEBRIEF)

- Did you notice anything unusual outside at any time while we were working with this navigation system?
    - Yes (circle)
        - What did you see?
        - Do you recall looking-up? Or did you just notice it in your peripheral vision?
        - When did you see it?
        - Did it happen more than once?
    - No (circle)
- At this point, I need to let you in on a secret. This study is not actually about navigation systems, but rather the attention-getting power of different types of rear brake lights.
- The navigation entry task served as a ruse to get you to divert your attention away from the lights located in front of us.
- We wanted to know whether the lights would attract your attention while you were distracted with the navigation entry task.
- Do you recall if you looked up, or noticed the lights?
    - Yes
    - No
- I'm sorry we tricked you, but this ruse was necessary in order to really understand if the lights would attract your attention.

(Informed Consent)

- From this point forward, we will be asking you to rate the attention-gettingness of different types of signal lights.
- First, I need you to read and sign this study consent form if you wish to continue. <hand them the informed consent>

Appendix D.

Characteristics of the Rear Lighting Used in the On-Road Rear Lighting Study (Chapter 4)

Outboard Lamp (Composed of 4 Individual Units)
(Measured using a Photopic Response Characteristic)

	On Axis Output at 8m	Equivalent On-Axis Output	Applied Voltage	Resulting Current
Imminent Warning Level (Measured for "on" portion of flash)	18.6 lux	1190 cd	13.9 v	1.085 a
Brake Level (Measured for "on" portion of flash or steady output)	2.38 lux	152 cd	8.7 v	0.15 a

CHMSL (Composed of 3 Individual Units)
(Measured using a Photopic Response Characteristic)

	On Axis Output at 8m	Equivalent On-Axis Output	Applied Voltage	Resulting Current
Imminent Warning Level (Measured for "on" portion of flash)	6.9 lux	442 cd	13.9 v	0.82 a
Brake Level (Measured for "on" portion of flash or steady output)	1.37 lux	87.7 cd	9.1 v	0.15 a

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