



U.S. Department  
of Transportation  
**National Highway  
Traffic Safety  
Administration**



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DOT HS 809 425

March 2002

# **Enhanced Rear Lighting and Signaling Systems:**

## **Literature Review and Analyses of Alternative System Concepts**

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1. Report No. DOT HS 809 425		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Enhanced Rear Lighting And Signaling Systems: Literature Review and Analyses of Alternative System Concepts				5. Report Date March, 2002	
				6. Performing Organization Code	
7. Author(s) Suzanne E. Lee, Walter W. Wierwille, and Sheila G. Klauer				8. Performing Organization Report No.	
9. Performing Organization Name and Address Virginia Tech Transportation Institute 3500 Transportation Research Plaza (0536) Blacksburg, VA 24061				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. DTNH 22-99-C-07235	
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration NHTSA, NRD-13 400 7th St SW Washington, DC 20590				13. Type of Report and Period Covered  Task 1 Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes Michael Perel was the NHTSA COTR for this project.					
16. Abstract <p>Rear-end crashes are the most frequently occurring type of collision, accounting for approximately 29% of all crashes and resulting in a substantial number of injuries and fatalities each year. Rear-end collisions in which the lead vehicle is stopped or moving very slowly prior to the crash account for the majority of these accidents. Over the years several initiatives have addressed the problem of rear-end crashes, with limited success. The most public of these ventures was the center high-mounted stop lamp (CHMSL), which was required to be present on automobiles beginning with model year 1986. The long-term effectiveness of the CHMSL has leveled off at about a 4% effectiveness in preventing rear-end crashes, which means there is still much room for improvement.</p> <p>The goal of this research effort is to develop and test a small number of enhanced rear-lighting concepts that have the potential to reduce the number of rear-end collisions. These are to include problems with stopped vehicles. This report encompasses the first task of the research effort. Task 1 involved investigating all previous efforts to develop enhanced rear-lighting systems, determining the causes of rear-end crashes, and developing a short list of rear-lighting alternatives to be tested in future research efforts under this project. The literature review revealed that numerous rear-lighting systems have been proposed over the past 30 years. Focus groups conducted with law enforcement officers found that the most common cause of rear-end crashes is driver inattention and distraction, with following too closely as the next most common cause. A review of several crash database analyses revealed similar results, as did a study in which drivers of striking vehicles were interviewed.</p> <p>The final subtask was to conduct a trade study to suggest two to three rear-lighting concepts for further study. An expert panel consisting of twelve rear-lighting experts was assembled. The trade study was conducted electronically (email) via a series of three questionnaires. This process resulted in the recommendation of three rear-lighting configurations for further refinement. Algorithms for the activation and deactivation of these systems were also developed during Task 1.</p>					
17. Key Words rear lighting, brake lights, rear-end crashes, rear signaling, focus groups, subject matter experts, trade study			18. Distribution Statement		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 139	22. Price



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## EXECUTIVE SUMMARY

Rear-end crashes are the most frequently occurring type of crash, making up approximately 29% of all crashes. There were an estimated 1,848,407 rear-end crashes in 1999, out of a total of 6,271,524 crashes (29.5%; General Estimate System, GES, database), resulting in 951,822 injuries (GES database) and 2,195 fatalities (Fatality Analysis Reporting System, FARS, database). Rear-end crashes in which the lead vehicle is stopped or moving very slowly prior to the collision are an especially serious problem, accounting for about two-thirds of all rear-end crashes. The magnitude of the rear-end crash problem has been a source of concern for a number of years, and much effort has been put forth to reduce this type of crash.

In the mid to late 1960s, the U.S. government funded five parallel efforts on alleviating the problem, primarily through enhancements to the rear-lighting systems of automobiles. These efforts did not result in any immediate changes to the rear-lighting system. However, they led to research in the mid 1970s through early 1980s, which was focused on the center high-mounted stop lamp, or CHMSL. By the mid 1980s all automobiles were required to be outfitted with CHMSLs, with vans, sport utility vehicles, and pick-up trucks following in 1993. Recent estimates of CHMSL effectiveness show that they reduce rear impact crashes by about 4% (Kahane and Hertz, 1998).

There have also been many smaller-scale efforts to address the problem of rear-end crashes over the years. Numerous papers have been written in research journals, numerous patents have been filed with the U.S. Patent and Trademark Office (USPTO), and numerous letters have been written to the National Highway Traffic Safety Administration (NHTSA). All of these inventors, researchers, and innovators have proposed concepts that they claim will reduce the number and/or severity of rear-end crashes, usually by means of enhanced rear lighting. The NHTSA policy for handling unsolicited ideas for rear-lighting systems has been published in the Federal Register, and is detailed within this report.

To help identify and evaluate rear-signaling concepts, NHTSA contracted with the Virginia Tech Transportation Institute (VTTI) to conduct a literature review, identify candidate signal system enhancements, and refine signal system performance requirements. The overall project objectives are as follows:

To perform comparative evaluations of alternative rear signal systems that might help drivers better detect and respond to stopped vehicles ahead. For the top two recommended signal systems, determine the signal characteristics most desirable from a human factors and practical perspective and develop prototypes. To evaluate the performance of drivers in response to the two signal system prototypes.

This report summarizes the Task 1 efforts in which an extensive literature review, law enforcement focus groups, and a trade-study were conducted. Each of these subtasks built on the previous subtasks in attempting to filter through the numerous ideas for enhanced rear-lighting systems to develop a small subset of ideas for optimization in Task 2. Optimization is expected to involve identification of a system or systems that maximizes attention-getting properties and minimizes negative effects such as glare and annoyance.

The literature review focused on reviews of several key areas: 1) previously conducted crash data analyses; 2) historical information on attempts to solve the problem; 3) published scholarly research; 4) patents and unpublished research. A final section of the literature review involved guidelines for warning signal design taken from the human factors literature. These are some of the conclusions reached from the literature review:

- Rear-end crashes are the most frequently occurring type of crash.
- Lead vehicle stopped crashes are the most common type of rear-end crashes.
- The majority of rear-end crashes occur 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 systems.
- Many of these ideas are similar, 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 the use of flashing, apparent motion, size, color contrast, and luminance contrast.

The next subtask was to conduct two focus groups with law enforcement personnel to gain their perspective on the contributing factors for and prevention of rear-end crashes. One group was conducted with officers from an urban environment and the other employed officers from small town/suburban environments. The focus groups provided insights into the causes and prevention of rear-end crashes, as well as the law enforcement procedures for dealing with these crashes. The most significant finding from the focus groups was that law enforcement officers perceive driver inattention and distraction to be the most frequent behavioral causes for rear-end crashes. This is consistent with findings from the crash database studies, as would be expected given that police crash reports form the basis of crash databases.

The final subtask was to conduct a trade study using an expert group to help identify which rear-lighting concepts have the greatest potential for being practical and effective crash countermeasures. The Kepner-Tregoe trade study technique was used. As implemented for the purposes of this project, the technique had three main steps. First, the criteria against which each alternative would be judged were developed with the help of the expert panel. Second, these criteria were divided into MUSTs and WANTS, with MUSTs being those criteria that each alternative must have in order to qualify for further consideration, and WANTS being those attributes that are desirable for the alternatives under consideration but which are not absolutely necessary. The only MUST criterion identified by the expert panel was that the concept “Addresses at least one causal factor associated with rear-end collisions.” Several WANTS were identified, such as that the concept “Improves driver perception of impending rear-end crashes by providing information to the following driver that a lead vehicle is stopped or moving slowly.” During the second step, the WANTS were also weighted according to their overall importance, again by the expert panel. In the third step, the concepts were presented to the experts, who rated them according to how well they met the MUSTs and WANTS criteria. In a final, in-house step, the weightings developed in step 2 were multiplied by the ratings provided

by the experts in step 3 to determine which alternatives had the highest overall score (and thus best met the criteria developed in step 1).

Between the second and third steps, VTTI researchers and expert panel members developed eight candidate rear-lighting concepts. The concepts incorporated features to enhance signal detection and to attract attention.

In the process of developing the concepts, an important distinction was drawn between open-loop and closed-loop systems, and also between rear signal countermeasures and forward collision warnings. In a closed-loop system, a detector (most likely radar based) is placed on either the rear bumper of the lead vehicle or the front bumper of the following vehicle. By measuring headway, closing rate, and possibly angle, a signal can be presented either on the rear of the lead vehicle or in the following vehicle (or both) whenever the headway is too short or the closing rate is too high. One advantage of a closed-loop system is that when the criteria for an impending collision no longer exist, the system can be deactivated (e.g., both vehicles have stopped, so the closing rate drops to zero for some predetermined amount of time and the signal turns off). This has the advantage of reducing annoyance in heavy traffic situations. Most importantly, closed-loop systems appear capable of precise determination of impending rear-end collisions.

In open-loop systems, the lead vehicle displays a signal based on predetermined parameters (e.g., degree of deceleration, brake activation, or vehicle stopped) and the driver of the following vehicle must perceive the signal and respond appropriately. There is no feedback loop between the vehicles (thus open-loop). In many cases the signal would remain activated as long as the parameter or parameters of interest are in the predetermined mode. For example, if the signal was a stopped vehicle signal, it would remain activated until the vehicle is moving again (although there is the possibility of timing out the open-loop activation.) If the signaling system is not timed out, a lower intensity signal might be required to diminish glare, annoyance, and light adaptation problems. Thus, the open loop systems is a challenge to design so that it helps prevent crashes yet does not cause any adverse effects due to glare and annoyance.

Three configurations were chosen as candidates for optimization (from the eight presented), based on the results of the expert panel trade study: Closed-loop, Radar Activated Horizontal Array of Lights; Open-loop, Horizontal Array of Lights Activated by Two Levels of Braking; and Closed-loop, Radar Activated High-Intensity Strobe Lights. From these three systems there are three eligible modes for testing: a sequential activation mode (lights activate from inside to outside in a horizontal array of lights), a continuous mode (a horizontal array of lights which remain continuously illuminated), and a flash mode (using strobes). In addition, it has been suggested that simpler rear-lighting enhancements, such as dual intensity signals, should be considered for evaluation.

One important subtask, carried out in parallel with the trade study analysis, was the development of algorithms for activation and deactivation of both open-loop and closed-loop systems. For closed-loop systems, a minimum range criterion was derived, and a logic flow diagram was developed for activation/deactivation of the system whenever this criterion is met. For open-loop systems, a logic flow diagram was developed that could be used in designing the system and testing it.

## **ACKNOWLEDGEMENTS**

This research was funded by the National Highway Traffic Safety Administration (NHTSA) under contract DTNH 22-99-C-07235. The Contracting Officer's Technical Representative (COTR) was Michael Perel.

The authors would like to acknowledge the help of certain individuals who lent their assistance and expertise in the completion of this Task 1 report:

- Michael Perel, Richard van Iderstine, and Michael Goodman of NHTSA for technical advice and project facilitation.
- Tom Dingus, Director of the Virginia Tech Transportation Institute (VTTI), for ensuring that the necessary organizational resources were made available.
- Richard Hanowski of VTTI who served as an internal reviewer and advisor.
- Eryn Perry of VTTI for literary editing and production of this document.
- Vivek Bhise (Ford Motor Company), Rollin Bible (3M Corporation), Stephen Brich (Virginia Dept. of Transportation), Jeffrey Calderas (General Motors Corporation), Theodore Cohn (University of California, Berkeley), Florian Dutke (General Motors Corporation), Jeffrey Erion (Visteon Corporation), Eugene Farber (Ford Motor Company, retired), Alan Lesesky (Vehicle Enhancement Systems, Inc.), Rudolf Mortimer (University of Illinois, Urbana-Champaign, retired), Louis Tijerina (Ford Motor Company), and Bradley van Riper (Truck-Lite Company, Inc.) for serving as members of the expert group. These individuals were very generous with their time and expertise.
- Members of the Alexandria (VA) Police Department, the Blacksburg (VA) Police Department, the Christiansburg (VA) Police Department, and the Virginia State Police for serving in the focus groups reported in this document. These individuals were candid, constructive, and creative.

### **Note Regarding Opinions Expressed**

The interpretive opinions expressed in this report are solely those of the authors and do not necessarily reflect the official position of any organization or the opinions of any other individual, including those acknowledged on this page.

## LIST OF ABBREVIATIONS

ABS	Antilock braking system
APD	Alexandria Police Department
BPD	Blacksburg Police Department
CHMSL	Center high-mounted stop lamp
CPD	Christiansburg Police Department
DWI	Driving while intoxicated (or impaired)
ECE	United Nations Economic Commission for Europe
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
GES	National Automotive Sampling System's General Estimates System
IES	Illuminating Engineering Society
KTA	Kepner-Tregoe Analysis
LVM	Rear-end crash in which the Lead Vehicle is Moving
LVS	Rear-end crash in which the Lead Vehicle is Stationary
NASS CDS	National Automotive Sampling System's Crashworthiness Data System
NCSA	National Center for Statistics and Analysis
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
USPTO	United States Patent and Trademark Office
VMT	Vehicle miles traveled
VSP	Virginia State Police
VTTI	Virginia Tech Transportation Institute

## INTRODUCTION

Rear-end crashes are the most frequently occurring type of crash, making up approximately 28% of all crashes. There were an estimated 1,848,407 rear-end crashes in 1999, out of a total of 6,271,524 crashes (29.5%; GES database), resulting in 951,822 injuries (GES database) and 2,195 fatalities (FARS database). Rear-end crashes in which the lead vehicle is stopped or moving very slowly prior to the collision are an especially serious problem, accounting for about two-thirds of all rear-end crashes. The magnitude of the rear-end crash problem has been a source of concern for a number of years, and much effort has been put forth to reduce this type of crash.

In the mid to late 1960s, the U.S. government funded five parallel efforts on alleviating the problem, primarily through enhancements to the rear-lighting systems of automobiles. These efforts did not result in any direct changes to the rear-signaling system. However, they appear to have led to the next effort in the mid-1970s through early 1980s, which was focused on the center high-mounted stop lamp, or CHMSL. By the mid-1980s all automobiles were required to be outfitted with CHMSLs, with vans, sport utility vehicles, and pick-up trucks following in 1993. Early estimates of effectiveness predicted that the CHMSL would reduce rear-end crashes by as much as 35% (Digges, Nicholson, and Rouse, 1985), but recent analysis of crash data indicate that the current effectiveness is closer to 4%. While this still represents obvious savings of life, injuries, and property, it means that there may be further opportunities to reduce the occurrence of rear-end crashes.

There have also been many smaller-scale efforts to address the problem of rear-end crashes over the years. Researchers, analysts, and inventors both in the United States and elsewhere have invested much time and effort in this problem. Often these individuals had hopes of financial gain if their idea was found to be effective in preventing rear-end collisions. Numerous papers have been written in research journals, numerous patents have been filed with the U.S. Patent and Trademark Office (USPTO), and numerous letters have been written to the National Highway Traffic Safety Administration (NHTSA), all purporting to have *the* solution, usually by means of enhanced rear lighting. There is an official NHTSA policy for handling unsolicited ideas for rear-signaling systems; this policy has been published in the Federal Register, and is detailed in a later section of this report. Given this policy, NHTSA has taken the path of focusing on the most prevalent, significant problem areas where rear-signaling might help. The current effort is the first step down this path.

There is a substantial problem with rear-end collisions, and there are numerous ideas for systems that might help prevent these collisions, but there are limited resources for testing these ideas. In particular, there is a problem with rear-end collisions into a stopped lead vehicle. Therefore, NHTSA contracted with the Virginia Tech Transportation Institute (VTTI) to conduct a study of the problem, suggest solutions, and conduct optimization and preliminary on-road tests of these solutions. This report summarizes the Task 1 efforts, in which an extensive literature review, law enforcement focus group meetings, and a trade-study were conducted. Each of these subtasks built on the previous subtasks in attempting to filter through the numerous ideas for enhanced rear-lighting systems to develop a small subset of ideas for optimization in Task 2.

All of the subtasks accomplished in Task 1 were in support of the primary objectives of Task 1, which were to:

- Generate an encompassing list of rear-signaling alternatives,
- Develop objective criteria for evaluating the alternatives, and
- Use a working group of experts to score the alternatives against the criteria to determine the two best alternatives for further study in Tasks 2 and 3.

The first subtask performed in support of these objectives was to conduct an extensive literature review focused on several key areas. Relevant literature was gathered from NHTSA, the Virginia Tech library and interlibrary loan systems, patent searches, and internet searches. The first question explored for the literature review was the size and scope of the rear-end crash problem. An in-house database analysis helped determine the prevalence of stopped lead vehicle rear-end crashes. Existing crash database analyses were reviewed to answer this question, and the database review also answered important questions about the contributing factors for rear-end crashes. Another important area of inquiry for the literature review was the historical record, in which previous attempts to solve the problem of rear-end crashes were examined. Especially relevant for the current study were the descriptions of the processes involved in introducing and assessing the effectiveness of the CHMSL.

Published scholarly research on the topic of rear-end crash prevention was then reviewed. There were relatively few papers of this type as compared to some of the other types of literature reviewed during this subtask. The next section of the literature review covered the patents and unpublished research. A large number of unsolicited letters and reports have been submitted to NHTSA over the years, each containing one or more ideas for reducing the frequency of rear-end crashes. An even greater number of rear-end crash prevention ideas was obtained during a series of patent searches. All of these ideas, published and unpublished, were reviewed to see if any concepts might have features which could help prevent rear-end crashes. A final section of the literature review involved guidelines for warning signal design taken from the human factors literature on this subject.

The key points derived from the literature review were:

- Rear-end crashes are a significant problem in terms of percentage of overall crashes, injuries and fatalities, and costs.
- Rear-end crashes in which the lead vehicle was stopped prior to the crash make up the majority of these crashes.
- The most common contributing factors cited by police for rear-end crashes are inattention (mental preoccupation), distraction (visual preoccupation), and following too closely.



- There is some historical precedent on methods for designing, evaluating, and introducing new rear-signaling systems.
- There are numerous ideas for systems intended to prevent rear-end crashes, both patented and unpatented.
- Very few of these ideas have undergone experimental evaluation.
- Many of the relevant scientific studies on this topic have been focused on database analysis, laboratory testing, and simulator testing, with very few on-road experiments.
- There are a number of human factors guidelines for the design of warning signals.
- These guidelines have not been used in a systematic fashion to synthesize rear-lighting designs which make effective use of known human perception and detection processes.

One of the more interesting findings from the literature review was the idea of primary contributing factors for rear-end crashes. Driver inattention, driver distraction, and following too closely have consistently been found by police reports to be the primary contributing factors. Some researchers, however, have speculated that human misperception of closing rate is a major factor for rear-end crashes, given the high proportion of such crashes that occur when the lead vehicle is stopped prior to the crash. A secondary data source was needed to resolve this contradiction, leading to the second subtask, law enforcement focus groups. These were conducted to gain a law enforcement perspective on the contributing factors for and prevention of rear-end crashes. The results reinforced the database analysis (perhaps not a surprising finding, given that databases are constructed from police crash reports). Officers first on the scene after a crash reported that inattention/distraction and following too closely were the primary contributing factors for rear-end crashes, with inattention/distraction being the most common factor. This was important information, not only because it supported the findings of the database review, but because the design of a rear-lighting system to prevent rear-end crashes depends on which driver behavior you are attempting to modify. A design intended to improve the detection of closing rate (which may bear some relationship to following too closely) could be quite different than a design intended to attract the following driver's attention.

The focus groups thus provided confirmation that an effective rear-signaling system needs to attract the following driver's attention, whether the driver is in a distracted state or is simply being inattentive. The literature review provided a wealth of rear-signaling concepts and human factors guidelines for how to attract attention, but left an important question unanswered: *What are the best systems for further testing?* A trade study was conducted to accomplish this goal. The specific technique used was the Kepner-Tregoe Analysis (KTA), a variant of the trade study technique. With the KTA technique, alternatives are evaluated against a list of NEEDs (mandatory) criteria. Those that meet the NEEDs criteria are then judged against a set of WANTs (desirable) criteria that have been assigned numerical ratings according to their importance in meeting the objectives of the analysis. Expert raters score the different alternatives on how well they meet the WANTs criteria (on a scale of 1-10). The numerical ratings are multiplied by the scores to get a weighted score for each criterion. The weighted

scores for each alternative are then summed to provide a numerical ranking of alternatives, which identifies one to three clearly preferred alternatives.

An important aspect of the trade study analysis is the use of experts to help develop the criteria and to score the alternatives against the criteria. An outstanding panel of rear-lighting experts was assembled, and they participated electronically (via email questionnaires). Three questionnaires were used. The first questionnaire resulted in a set of criteria against which the candidate rear-signaling concepts would be judged. The second questionnaire had the experts rate the criteria according to importance to the overall goal of reducing rear-end crashes.

At this point an important juncture was reached. The experts were assembled and the criteria were ready, but there was no clear list of candidate concepts. The experts had been given the opportunity to suggest concepts during each of the first two questionnaires, but provided no ideas that were new to the researchers (after having performed the literature review). Thus the VTTI researchers were forced to devise candidate concepts, using what was known and had been learned about human perception. Given that the following driver's attention needs to be captured, there are specific methods for accomplishing this using color coding, shape coding, flash coding, size coding, and apparent motion. The use of redundant coding is also important for any warning system. The researchers used these guidelines to create a set of eight unique, redundantly coded rear-lighting concepts designed to capture the following driver's attention.

Once the concepts had been developed, the expert panel was presented with the third questionnaire in which they were asked to rate each concept according to the previously developed criteria. The ratings were then multiplied and summed according to the KTA procedure.

It is believed that the combination of a good analytical technique (KTA trade study analysis) and a strong working group of experts resulted in the identification of the best rear-lighting alternatives for further study in Tasks 2 and 3. The expert panel selected the following three concepts as the best enhanced rear-lighting configurations (from the eight presented): Closed-loop, Radar Activated Horizontal Array of Lights; Open-loop, Horizontal Array of Lights Activated by Two Levels of Braking; and Closed-loop, Radar Activated High-Intensity Strobe Lights. Therefore, the lighting optimization process to be carried out in Task 2 should include at least these three configurations. From these three systems there are three eligible modes for testing: a sequential activation mode (lights are activated from inside to outside in a horizontal array of lights), a continuous mode (a horizontal array of lights which remain continuously illuminated), and a flash mode (using strobes). These are the modes likely to be recommended for optimization in the test plan for Task 2, perhaps with the addition of a simpler signal now under development.

## LITERATURE REVIEW

### Goals of the Literature Review

As discussed during the introduction, the literature review is but one piece of the framework for selecting rear-lighting concepts for further evaluation (the primary goal of Task 1). Together with the law enforcement focus groups and the expert panel trade study, the literature review provides important input for the design and selection process.

In attempting to address a problem of the size and scope of rear-end crash prevention and rear-lighting enhancements, there are many issues to be explored and questions to be answered. Fortunately, a large body of literature has been developed over the past 35 years that addresses these issues and attempts to answer these questions.

- Size and shape of the problem: Crash database analyses
  - What percent of crashes are rear-end crashes?
  - What percent of fatal crashes are rear-end crashes?
  - What are the characteristics of rear-end crashes?
  - What percentage of rear-end crashes occur when the lead vehicle is stopped prior to the crash?
  - Under what scenarios do rear-end crashes occur?
  - What are the documented contributing factors for rear-end crashes?
- Historical perspective
  - What previous initiatives have been conducted on the problem of rear-end crashes?
  - What were the results of these initiatives?
  - What are the lessons from the CHMSL experience?
  - What is the current NHTSA policy for unsolicited rear-signaling ideas?
- Previous academic research results
  - What types of research have been conducted on rear-lighting enhancements?
  - What were the results of this research?
  - Has there been research on other rear-end crash countermeasures?
- Patents
  - What patents have been issued for rear-signaling enhancements?
  - What areas do these patents cover?
- Human factors considerations
  - What guidelines are there for the development of enhanced rear-signaling systems?

The first sections of the literature review cover work published in the open literature. The next sections encompass patents and unpublished materials. The final section contains a review of human factors guidelines applicable to the design of rear-lighting systems.

## **Database and Statistical Assessment**

According to numerous crash database analyses, 25-30% of all collisions on U.S. highways are rear-end collisions (e.g., General Motors, 1997). Rear-end collisions are commonly separated into two groups: rear-end collisions where the lead vehicle is moving (LVM) and rear-end collisions where the lead vehicle is stopped (LVS). Statistics concerning the problem size, demographic information, common collision scenarios, leading causes, and limited data on avoidance maneuvers in rear-end collisions will be discussed in this section.

There are several different databases that compile information about automobile crashes in the United States. The primary statistical sources that most of the following analyses are based upon are:

- National Automotive Sampling System: General Estimates System (GES)
- Fatality Analysis Reporting System (FARS)
- National Automotive Sampling System: Crashworthiness Data System (NASS CDS)
- National Center for Statistics and Analysis (NCSA) *Accident Facts*

The NASS GES is a database compiled by NHTSA. Police reported crashes occurring in the United States that result in property damage, injury, or death are sampled according to a statistical sampling plan. The crashes entered into the database are each assigned a weight so that national estimates can then be developed for each type of crash. The FARS databases are also compiled by NHTSA. The FARS databases contain statistics on police-reported crashes in the U.S. that result in at least one fatality to a motorist or non-motorist (which occurred within 30 days of the crash). The NASS CDS has detailed data on a sample of thousands passenger vehicle tow-away crashes. Field research teams study about 5,000 crashes a year using intensive field investigation with follow-up interviews of crash victims and reviews of medical records to determine the nature and severity of injuries. The GES database was initiated in 1988, while FARS was started in 1975 and NASS CDS began in 1979. The NSCA's *Accident Facts* is compiled using information from both the GES and FARS databases. These databases have been used by transportation researchers to determine the problem size of and contributing factors for motor vehicle crashes on the nation's highway and interstate system.

### Problem Size of Rear-End Collisions

Wiacek and Najm (1999) conducted a database study using the General Estimates System (GES) crash database for the years of 1992 through 1996. Among other findings, they reported that rear-end collisions were the most frequent type of crash for this time period, accounting for nearly 25% of all crashes in the U.S.

Knipling, Hendricks, Koziol, Allen, Tijerina, and Wilson (1992) reported that there were 1.5 million police reported rear-end crashes in 1990. This constituted 23% of all crashes and 5% of all fatalities on U.S. highways (GES and FARS databases). There were 800,000 injuries associated with these rear-end collisions, most of which were of mild severity. Rear-end crashes were separated into LVS and LVM statistics as shown in Table 1. It is important to note that

there are significantly more LVS crashes than there are LVM crashes, and LVS crashes led to 300 more fatalities in 1990 than did LVM crashes.

**Table 1. Rear-end collision statistics from the 1990 GES database.**

<b>Crash Subtype: Statistic and Source</b>	<b>Rear-End Lead Vehicle Stationary (LVS)</b>	<b>Rear-End, Lead Vehicle Moving (LVM)</b>
Annual Police-Reported (PR) Crashes	1.05 million	0.46 million
Annual Non-Fatal Injuries in PR Crashes	570,000	240,000
Percent of All PR Crashes	16.2%	7.1%
Annual Fatalities*	1,600	1,300
Fatalities Per PR Crash**	0.0016	0.0030

Adapted from Knipling, Hendricks, Koziol, Allen, Tijerina, & Wilson (1992).

\* Rear-end crash LVS vs. LVM unknowns (about 11% of the total) have been distributed proportionately across subtypes so that the LVS + LVM total equals all rear-end crashes.

\*\* GES fatality statistics are used in this table because FARS does not differentiate LVS from LVM crashes. The FARS count for all rear-end crash fatalities in 1990 was 2,078. Imputing the GES LVS vs. LVM proportion to the FARS total rear-end crash fatality count yields estimates of 1,146 LVS fatalities and 932 LVM fatalities for 1990. The associated fatalities/PR crash proportions for LVS and LVM crashes are 0.0011 and 0.0020, respectively.

McGehee, Dingus, and Mollenhauer (1994) reported that 23.8% of all crashes were rear-end collisions based on a review of the NASS CDS and the NSCA's *Accident Facts* for 1991. When the rear-end collisions were separated into LVM and LVS, the LVS crashes accounted for 69.7% of all rear-end collisions.

Yet another study found that rear-end crashes were the most frequently occurring crash type in the U.S. (1,454,000 or 23.2%) based on the GES databases for 1989-1993. Rear-end crashes were also found to be the second most costly type of crash, costing U.S. citizens \$35.2 billion per year (Wang, Knipling, & Blincoe, 1996). Table 2 lists the number of crashes and cost of LVS and LVM collisions for a number of different statistical categories.

These four database analyses of crashes from 1990 through 1996 all demonstrated that rear-end collisions are the most frequent type of crash, that they constitute approximately one-fourth of all collisions, and that they are the second most costly crash type for U.S. citizens. Recent indications are that the percentage of rear-end crashes is increasing, even as the overall numbers remain fairly steady at about 1.85 million rear-end crashes per year (Table 3). Lead vehicle stationary collisions occur more frequently and result in more fatalities than do lead vehicle moving crashes. Understanding these crashes, including the primary contributing factors, could perhaps result in countermeasures to reduce their incidence. This would result in savings of human life and human suffering, as well as financial savings.

**Table 2. Statistics on two types of rear-end collisions in the United States.**

<b>Statistics</b>	<b>LVS</b>	<b>LVM</b>
Annual # of PR crashes	974,000	480,000
Annual # of persons involved in PR crashes	3,107,000	1,522,000
Not injured	2,469,000	1,212,000
Minor to moderate injuries	618,000	299,000
Serious to fatal	20,000	11,000
Annual U.S. monetary cost (\$)	(E) 23.3 billion (C) 346.1 billion	(E)11.9 billion (C)24.7 billion
Average U.S. Monetary Cost Per PR crash (\$)	(E) 14,127 (C) 32,721	(E) 14,962 (C) 36,200
Per 100 million VMT (\$)	(E) 1,062,422 (C) 2,102,510	(E) 544,789 (C) 1,127,003
Per registered vehicle annually (\$)	(E) 126 C 249	(E) 65 (C) 135
Expected monetary cost Per vehicle over driving career (\$)	(E) 1,365 (C) 2,702	(E) 700 (C) 1,448
Per driver over driving career (\$)	(E) 9,681 (C) 19,159	(E) 4,964 (C) 10,270
Total annual national fatal equivalents	15,735	8,434
Average fatal equivalents per PR crash	0.01118	0.01236
Expected fatal equivalents over vehicle life	0.00092	0.00049

E = Economic Cost; C = Comprehensive Cost; PR = Police-Reported; VMT = vehicle miles traveled

**Table 3. Percent of rear-end crashes over the past six years from the GES database.**

<b>Crash data</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>
GES, total all crashes	6,489,122	6,690,061	6,761,051	6,611,906	6,325,242	6,271,524
Rear-end crashes	1,753,996	1,845,379	1,904,709	1,871,564	1,871,271	1,848,407
Percent of crashes that are rear-end crashes	27.0%	27.6%	28.2%	28.3%	29.6%	29.5%

### Statistics Analyzed by Age and Gender

Wiacek and Najm (1999) analyzed the 1996 GES database for age and gender factors for rear-end crashes. This study suggested that drivers less than 24 years old are overly involved in rear-end collisions, in that they represent 21% of all drivers yet are involved in 30% of all rear-end collisions. Drivers over age 64 are under-involved in rear-end collisions; this age group represents 13% of all licensed drivers, yet is involved in only 6% of all rear-end collisions. This finding may suggest that rear-end collisions are not the direct result of drivers' reaction times or overall driving abilities, because younger drivers generally have faster reaction times than do older drivers. Wiacek and Najm also conducted an analysis of gender involvement in rear-end crashes. Their results suggest that males are slightly over-represented in rear-end collisions. Males constitute 53% of the driving population, yet are involved in 60% of all rear-end crashes. Note that these studies do not account for exposure differences among age or gender groups, and thus, for example, older drivers might be over-involved in other types of crashes on a miles driven basis.

Another study by Knipling, Wang, and Yin (1993) used data from the 1990 GES and FARS crash databases. The results on gender involvement were categorized by involvement as either the striking vehicle or the struck vehicle in a rear-end collision. These results are shown in Table 4. While both males and female drivers are equally represented in the striking vehicle, female drivers of struck vehicles are over-represented. This could be due to a lingering vestige of demographic differences between males and females with respect to driving.

**Table 4. Rear-end collision statistics on gender and role of vehicle.**

<b>Role of Vehicle</b>	<b>Male Drivers</b>	<b>Female Drivers</b>
Striking Vehicle	61.4 per 100 million VMT	61.5 per 100 million VMT
Struck Vehicle	62.8 per 100 million VMT	86.9 per 100 million VMT

Adapted from Knipling, Wang, & Yin (1993).

These two research studies present somewhat conflicting results that suggest that gender may not play an important role in rear-end collisions. Also, in most cases, the striking vehicle is charged with a driving violation or is considered to be at fault, and this is perhaps more pertinent to the present research focus; gender of the striking vehicle driver was approximately equal in the Knipling et al. (1993) study.

### Common Scenarios for Rear-End Collisions

Given that rear-end collisions are the most frequently occurring type of collision, a great deal of research has been conducted to define the types of scenarios in which they occur. Misener, Tsao, Song, and Steinfeld (2000) conducted a study of LVS crashes and isolated the four most common roadway geometry scenarios:

- Near intersection; struck vehicle at or near an intersection; 43% of LVS crashes.
- Midblock; struck vehicle stopped due to traffic congestion or at the end of a long queue waiting to pass through intersection; 31% of LVS crashes.

- Freeway; struck vehicle stopped on freeway; 18% of LVS crashes.
- Non-intersection junction; struck vehicle stopped at a non-intersection junction (i.e., a junction between a regular roadway and a driveway, alleyway, or ramp); 8% of LVS crashes.

Wiacek and Najm (1999) also isolated five of the most frequently occurring scenarios using the 1996 GES database for both LVS and LVM crashes. However, they looked at a combination of lead vehicle behaviors and roadway geometries. The five most common combinations of behaviors and geometries are listed in order of frequency:

1. *Lead vehicle decelerates, straight road.* Both the following and lead vehicles are traveling at a constant speed on a straight road and the lead vehicle then decelerates; 37.0%.
2. *Lead vehicle stopped, straight road.* The following vehicle is traveling at a constant speed on a straight road and encounters a lead vehicle stopped in the traffic lane ahead; 30.2%.
3. *Lead vehicle slower, straight road.* The following vehicle is traveling at a constant speed on a straight road and encounters a lead vehicle traveling at a constant, lower speed ahead; 14.1%.
4. *Lead vehicle decelerates more, straight road.* Both the following and lead vehicles are decelerating on a straight road and the lead vehicle then decelerates at a higher rate; 4.5%.
5. *Lead vehicle stopped, curved road.* The following vehicle is traveling at a constant speed on a curved road and encounters a lead vehicle stopped in the traffic lane ahead; 3.0%.

McGehee, Dingus, and Mollenhauer (1994) used the 1992 NASS CDS database and isolated 15 dynamic situations involving five behaviors of the lead vehicle (stopped; constant velocity; decelerating; accelerating; and decelerating and stopped) and three behaviors of the following vehicle (accelerating, constant velocity, and decelerating). Of the resulting 15 dynamic situations, the scenarios presented in Table 5 occurred most frequently.

**Table 5. Dynamic situations in rear-end collisions as described by McGehee, Dingus, and Mollenhauer (1994).**

<b>Rank</b>	<b>Lead Vehicle</b>	<b>Following Vehicle</b>	<b>Percent Occurrence</b>
1	Decelerating and stopped	Constant velocity	50.1%
2	Stopped	Constant velocity	23.7%
3	Decelerating	Constant velocity	14.7%
4	Decelerating and stopped	Decelerating	4.6%
5	Constant velocity	Constant velocity	2.8%



DaSilva and Najm (1999) conducted an analysis of precrash scenarios for rear-end collisions. The precrash scenario was operationally defined as the behavior of the lead vehicle prior to the crash. Their findings, based on the GES databases for 1992-1996, suggest that the three major driving behaviors occurring prior to rear-end collisions were:

- Lead vehicle decelerating: 37.9%
- Lead vehicle stopped: 33.2%
- Lead vehicle slower: 15.0%

The analyses just described indicate that most rear-end collisions occur when the lead vehicle is decelerating, decelerating to a stop, or is stopped. (Note that the GES coding manual specifies that the “stopped in traffic lane” code be used “if the vehicle is **not** in motion on a roadway.” No mention is made of the length of time that the vehicle in question was stopped.) These crashes occur on straight roadways as well as at or near intersections. A smaller percentage of rear-end collisions occur mid-block in residential areas, as well as on freeways. Solomon, Preusser, and Leaf’s (1996) study of the Washington, DC beltway found that 36% of all collisions on the beltway were rear-end collisions, and a high percentage of these collisions occurred on ramps. More specifically, high percentages of rear-end collisions were found to occur on specific ramps. These results may suggest that the geometric design of roadways can directly influence the number of rear-end collisions occurring in specific areas.

One puzzling finding is that the problem size analysis (first section of this discussion) suggested that most rear-end collisions occur when the lead vehicle is *stopped*, whereas the studies just discussed suggest that most collisions occur when the lead vehicle is *decelerating or decelerating to a stop*. This contradiction may be related to the imprecise nature of the information found in the crash databases, or it may result from the analysis methodology. Most of the studies which cite a greater percentage of lead vehicle decelerating rear-end crashes use the methodology of Wiacek and Najm (1999). A careful review of this methodology reveals that it represents an attempt to discern the *pre-crash* scenarios of rear-end crashes. Wiacek and Najm inferred the pre-crash state in the following manner:

Our analysis of rear-end crashes listed the lead vehicle as ‘decelerating’ to a stop if its dynamic state was coded as Stopped in Traffic Lane on a straight road either due to a traffic control device or in order make a turn. (Wiacek and Najm, 1999, p.2)

This means that if a vehicle were stopped at a traffic light for one minute prior to being struck by another vehicle from the rear, the pre-crash scenario would be listed as “decelerating to a stop.” This method of inference seems rather imprecise. In an attempt to shed light on this matter, a database analysis was conducted using the 1997-1999 GES vehicle data files. Of interest was the action of a struck vehicle prior to the collision, when the initial impact was in the rear of the vehicle (this implies the scenario of a lead vehicle struck in the rear). This analysis brings the question to its simplest form: *what was the lead vehicle doing just prior to being struck by a following vehicle?* Table 6 shows that approximately 59% of lead vehicles involved in rear-end

crashes in this time period were stopped in the traffic lane prior to being struck. Again, the database makes no distinction for the length of time that the lead vehicle was stopped prior to being struck. This finding highlights the possible need for a stopped vehicle signal, albeit one that is capable of attracting the attention of an inattentive or distracted following driver.

**Table 6. Movement of struck vehicle prior to critical event, where initial impact was back of vehicle (GES 1997-1999).**

	1997		1998		1999	
	Total	Percent	Total	Percent	Total	Percent
Going straight	236,909	12.6%	236,644	12.8%	154,720	8.6%
Decelerating in traffic lane	332,383	17.7%	305,633	16.5%	340,436	18.9%
Starting in traffic lane	16,354	0.9%	17,866	1.0%	26,487	1.5%
<b>Stopped in traffic lane</b>	<b>1,083,851</b>	<b>57.9%</b>	<b>1,078,822</b>	<b>58.4%</b>	<b>1,120,010</b>	<b>62.3%</b>
Passing or overtaking another vehicle	1,026	0.1%	354	0.0%	1,177	0.1%
Disabled or parked in travel lane	6,759	0.4%	7,401	0.4%	5,463	0.3%
Turning right	55,804	3.0%	60,150	3.3%	37,325	2.1%
Turning left	57,901	3.1%	64,480	3.5%	30,494	1.7%
Other and unknown	82,410	4.4%	76,930	4.2%	85,436	4.8%
<b>Total</b>	<b>1,873,396</b>	<b>100.0%</b>	<b>1,848,280</b>	<b>100.0%</b>	<b>1,798,226</b>	<b>100.0%</b>

#### Possible Contributing Factors for Rear-End Collisions

Using the GES databases from 1994 and 1997, Misener, Tsao, Song, and Steinfeld (1999) used statistical methods and filtering techniques to narrow down a comprehensive list of possible crash contributing factors. Their technique isolated the following important factors in rear-end collisions:

- *Driver impairment.* Not in the traditional sense, as only 3-5% of LVS crashes involve a driver impaired by alcohol. Rather, this variable allows a glance away from the road of up to 1.5 seconds, for modeling purposes (based on unimpaired driver behavior).
- *Driver age.* Drivers age 15-19 have a slightly higher exposure risk for rear-end crashes than all other age groups combined.
- *Crash trajectory.* In the majority of cases, the striking driver takes no corrective action prior to striking a stopped vehicle (note that this finding implies that the problem is more one of inattention and distraction, rather than failure to perceive the closing rate). When corrective action is taken, it is always a braking action, occasionally accompanied by a steering action.
- *Speed of striking vehicle.* The median speed in non-freeway scenarios is 22 mph.

- *Roadway surface.* Most LVS crashes occur on dry roadway surfaces, so attention should be directed towards this condition first.
- *Visibility/lighting.* Most LVS crashes occur during daylight hours, so attention should be directed towards this condition first.
- *Braking.* The mean braking force for dry pavement for 1994-95 model passenger cars was 0.867g.

Note that Misener et al. labeled glances away from the road as “driver impairment,” while most other studies have labeled this behavior as “driver inattention or distraction.” These other studies have also found driver inattention to be the most common cause of rear-end collisions.

Knipling, Hendricks, Koziol, Allen, Tijerina, and Wilson (1992) analyzed 74 rear-end collisions found in the 1991 NASS CDS database. The researchers separated rear-end collisions into LVS and LVM crashes and found that driver inattention was the number one cause of collisions for both types. Table 7 presents the relevant factors from this analysis.

**Table 7. Ranking of principle causal factors in two types of rear-end collisions.**

<b>Crash Subtype: Principle causal factor</b>	<b>Lead vehicle stationary number (percentage)</b>	<b>Lead vehicle moving number (percentage)</b>
Driver inattentive	39 (68.4%)	9 (52.9%)
Driver inattentive and following too closely	6 (10.5%)	2 (11.8%)
Following too closely	5 (8.8%)	1 (5.9%)
Alcohol involvement	5 (8.8%)	1 (5.9%)
Miscellaneous other	2 (3.5%)	4 (23.5%)
<b>Total cases</b>	<b>57</b>	<b>17</b>

\*Adapted from Knipling, Hendricks, Koziol, Allen, Tijerina, & Wilson (1992).

McGehee, Dingus, and Mollenhauer (1994) found similar results in an analysis of the 1991 NASS CDS database. Sixty-three percent of all rear-end collisions were caused by driver inattention, 15% were alcohol related, 14% were a result of inattention and following too closely, 2% were due to poor judgment, and 3% were due to poor visibility. The authors separated these factors into two *behavioral* factors for rear-end collisions and three *perceptual* factors. Driver inattention and following too closely were cited as the two most frequent driver behaviors that contributed to rear-end collisions. The perceptual factors included distance perception and rate of closure.

Wang, Knipling, and Goodman (1996) analyzed the 1995 NASS CDS database and found that the three most prevalent known causes of rear-end collisions were driver distraction, inattention (looked-but-did-not-see), and fatigue (Table 8).

**Table 8. Causes of rear-end collisions from an analysis of the 1995 NASS CDS.**

<b>Crash type</b>	<b>Sleepy</b>	<b>Distracted</b>	<b>LBDNS</b>	<b>Unknown</b>	<b>Attentive</b>
Lead vehicle moving	12.7%	21.3%	3.4%	48.3%	14.3%
Lead vehicle stopped	Too few cases	23.9%	11.4%	52.6%	11.8%

Najm, Koziol, Tijerina, Pierowics, and Hendricks (1994) conducted an analysis of five major crash types. They analyzed the crash types by problem size and contributing circumstances, among other items, and developed a model to determine the effectiveness of IVHS countermeasures. In the analysis, the following were found to be contributing factors for rear-end collisions (factors listed in order of importance):

1. Recognition errors (56.7%)
2. Decision errors (26.9%)
3. Drowsy and ill drivers (9.6%)
4. Roadway (2.3%)
5. Alcohol (2.1%)
6. Vehicle (1.2%)
7. Erratic actions (1.1%)
8. Atmospheric visibility (0.1%)

For the purposes of the Najm et al. (1994) study, recognition errors included driver inattention, looked-but-did-not see, improper lookout, internal and external distraction, vision obstructed by intervening vehicles, roadway geometry, and roadway appurtenances. Decision errors included such behaviors as misjudged gap/velocity of approaching vehicles, tailgating, and driving at excessive speeds.

One final study found the following breakdown causation for rear-end collisions: driver inattention (56.7%), tailgating/unsafe passing (26.5%), illness (9.6%), bad roadway (2.3%), and drunk driving (2.1%). This study by Najm, Mironer, Koziol, Wang, and Knipling (1995) used data from the 1991-1993 GES databases. The authors stated that crashes in which both tailgating and driver inattention played a role accounted for nearly 20% of all rear-end collisions. In their subjective judgment, tailgating was the primary cause of rear-end crashes.

Note that the above studies all rely heavily on police reports since they are derived from crash databases, which are constructed using police reports. Another approach for finding the causes of rear-end crashes would be to question the drivers of the striking vehicles. This can be difficult to do, as shown by Kostyniuk and Eby (1998), who conducted a pilot study that examined rear-

end crashes from the drivers' perspective to gain insight into the factors behind these crashes. The goals of the pilot study were to:

- Identify self-reported reasons why rear-end crashes occur.
- Identify how these driver-reported reasons relate to certain situations and locations.
- Identify crash hazard cues drivers recognized or failed to recognize.
- Determine whether this approach has merit for developing countermeasure ideas.

The study was conducted using focus groups of three age categories of drivers. It proved extremely difficult to recruit participants. Out of an initial subject pool of 660 drivers of the striking vehicle in a rear-end crash, only 30 agreed to participate, and of these, only 16 actually showed up for the focus group sessions. Of the 14 who failed to appear, 10 later agreed to be interviewed by telephone, for a total of 26 participants. Because the focus groups had small numbers of subjects, they were also conducted in a manner similar to interviews.

Drivers' responses to the causal factors leading to the crash varied according to how the question was asked. Drivers often gave one response when asked the cause (question based factors), and another when asked to describe the sequence of events leading up to the crash (explanation-based factors). The most common question-based factor described by the drivers was the action of the other driver (49%; examples include: stopped unexpectedly, did not move when it should have, did "strange things"). The next most common question-based factor was personal error (31%), which included personal inattention and distraction. The other question-based factors were road design (7%), environment (9%), and vehicle problems (4%). Explanation-based factors differed from the question-based factors, both in nomenclature and distribution, with divided attention accounting for 32%, incorrect assumptions about the lead vehicle accounting for 40%, and "unavoidable" accounting for 28%.

Of the suggested countermeasures provided by drivers, two are of interest to this report. One suggestion was for "a device to let you know if the car ahead is slowing down or not moving," and the other suggestion was for "a device that would not let you move if the car immediately ahead was not moving." Note that the latter suggestion would require between-vehicle telemetry. One of the authors' conclusions was that "An unambiguous indication of the stopped status of the vehicle was clearly needed" (Kostyniuk and Eby, 1998, p. 20).

Based on these studies, driver inattention (called driver impairment in one study) and following too closely were cited repeatedly as the most common contributing factors for rear-end collisions. These studies examined a variety of databases from 1990 through 1997, as well as driver reported causes (albeit from a sample of 26 participants). These findings will play a crucial role in the development of new rear-signaling systems for this project. To put these findings in the form of research questions: *how can we get the following driver's attention, and how can we get the following driver to follow at a safe distance?*

### Avoidance Maneuvers

Wiacek and Najm (1999) performed a study that analyzed avoidance maneuvers found in the crash reports from the 1996 GES database. These findings suggested that in over 78% of rear-end crashes, no action was taken. The only exception was when both the following and lead vehicles were decelerating on a straight roadway, in which case 68% of the following drivers took no action. If action was taken, the most common action was braking, but this occurred only 14.5% of the time. This finding appears to be directly related to the previous finding that most rear-end collisions are caused by driver inattention and following too closely. It may be that drivers never even realize that a collision is imminent and thus do not act to prevent the collision. If the following driver's attention can be gained and he or she can be prevented from following too closely, the driver would gain time to react to the impending collision. If a failure to detect closing rate was the primary contributing factor for rear-end crashes, then one might expect that the closing rate would be detected at some point before the collision, and thus some form of corrective action taken before the collision.

### Vehicle Types

Most vehicles involved in rear-end crashes are passenger vehicles (e.g., in 1998, approximately 3,500,000 light vehicles were involved in rear end crashes, as compared to 78,000 commercial vehicles; Barr, 2001). In most respects, the rear-end crash parameters are nearly identical in their statistical distributions between commercial vehicles and light vehicles. For example, approximately 67% of rear-end crashes involving light vehicles occur in daylight and clear weather, while approximately 69% of rear-end crashes involving commercial vehicles occur in these conditions (Barr, 2001). The main difference is in the "struck vehicle" versus "striking vehicle" categories. As might be expected, light vehicles are represented in the struck and striking categories about equally. When a commercial vehicle is involved in a rear-end crash, however, it is the striking vehicle approximately 61% of the time (based on 1998 and 1999 data compiled by Barr, 2001). The fact that more commercial vehicles are the striking rather than the struck vehicle in rear-end crashes is probably related to the physics of heavier vehicles and their longer stopping distances. Given these longer required stopping distances, a rear-signaling concept applied to light vehicles that is more noticeable from a greater distance has the potential to reduce the incidence of commercial vehicles striking light vehicles. These rear-end crashes have the greatest injury and fatality potential due to the heavier mass of most commercial vehicles, and thus the positive effect of increased stopping time or stopping distance could be highly beneficial.

### **Development and Evaluation of Rear-Signaling Systems**

A significant body of research on rear-signaling systems was conducted in the 1960s, and this led to the current standards and regulations governing rear-signaling systems. The only major development in rear-signaling systems since then has been the addition of the center high-mounted stop lamp (CHMSL) in the 1980s; the effectiveness of CHMSLs will be reviewed in this section. Other topics covered in this section include: the standardization and current regulations for rear-signaling systems, design and evaluation methodologies used in creating new rear-signaling systems, and design guidelines that have been proposed for rear-signaling systems.

### Standardization/Regulations of Rear-Signaling Systems

Various organizations in the United States and elsewhere are involved in developing standards for rear-signaling systems. Europe and the United States have played leading roles in this standardization. However, the relevant regulatory agencies differ in sponsorship and scope of authority.

The Society of Automotive Engineers (SAE) has maintained a committee on vehicle lighting standards since the early twentieth century and has taken a leadership role in the United States. The Illuminating Engineering Society (IES) was founded one year after the SAE Lighting Committee, and the two organizations jointly published the first automobile lighting standard in 1918 (Moore & Rumar, 1999). In the 1960s, the United States government established the predecessor of the National Highway Traffic Safety Administration (NHTSA). By 1970, NHTSA had published the Federal Motor Vehicle Safety Standard (FMVSS 108), which incorporated many SAE standards including several for rear-lighting (Table 9). In Europe, the United Nations Economic Commission for Europe (ECE) establishes the lighting regulations.

**Table 9. SAE rear-lighting standards incorporated in 1970 FMVSS 108.**

<b>SAE Standard Number &amp; Date</b>	<b>Subject</b>
J585c, June 1966	Tail lamps
J586b, June 1966	Brake lamps
J588d, June 1966	Turn signal lamps
J593c, February 1968	Back up lamps
J587d, March 1969	License plate lamps

### Development and Evaluation of Rear-Signaling Systems

The U.S. government sponsored several studies of rear-lighting systems in the mid to late 1960s. Some of these studies were focused both on developing new systems and on evaluating driving performance using the new rear-lighting systems, while other studies concentrated on *either* the development *or* evaluation of rear-lighting systems. Several of the current rear-lighting standards were based on this body of research.

Case, Hulbert, Lyman, O'Brian, and Patterson (1968) conducted a study for the U.S. Department of Transportation in which a new vehicle rear-lighting system was developed and evaluated. This research effort was the first to consider rear-signaling as a system, including brakes, turn signals, running lights, etc., rather than investigating each component separately. One important aspect of this report is that it outlined a methodology similar to the one being used for the current study, including determining the drivers' needs, developing rear-lighting concepts to meet those needs, performing a trade-off analysis using lighting experts, developing two systems for mock-up and further evaluation, and testing these systems in an experimental setting. The Case et al. report also contained a set of design guidelines that will be discussed in the design guideline section of this report.

Nickerson, Baron, Collins, and Crothers (1968) also performed a review of the rear-lighting problems for the U.S. Department of Transportation. Their report discussed two types of

approaches to investigating the problems of rear-lighting in U.S. automobiles: either make incremental improvements to current standards, or perform a full systems evaluation and develop alternative lighting systems. The first approach is practical and feasible, but is shortsighted in the long-term. The second approach is somewhat impractical, but a systems understanding of the problem is essential to solving the current problems.

The authors further developed the rear-lighting system as an *information-transmitting system*, capable of delivering the following information: presence of a vehicle, application of a brake pedal, impending turn, vehicle in reverse gear, and a cautionary (hazard) signal. The authors suggest that the information-transmitting system also needs to transmit the following information: advance warning of brake application, an indication of the vehicle's velocity, and an indication of the rate of deceleration.

Projector, Cook, and Peterson (1969) evaluated several other FHWA contractor's reports on rear-lighting systems, and then developed a unique rear-lighting system to be used in U.S. automobiles. The authors proposed a rear-lighting system based on the research, recommendations, and guidelines from four independent contractors: Bolt, Beranek, & Newman, Inc., Ohio State University, University of California at Berkeley, and University of California at Los Angeles.

Their unique design consisted of a *sideways T* design of lights on each side of the vehicle (Figure 1). Within this 'T' shape, three red running lights would be horizontally arranged with a red stop lamp above the running lights. The stop lamp would have a black matte surface surrounding it. The running light directly under the stop lamp would also contain a yellow turn signal. The other turn signal would be located directly below the first turn signal lamp. All lights, except the top stop lamp, would be surrounded by a Class A retroreflector. The stack of three vertical lamps would wrap around the rear corner of the vehicle so that drivers in the adjacent lanes and intersections would also be able to detect the turn signals and stop lamps.



**Figure 1. The proposed rear-signaling system of Projector, Cook, & Peterson (1969). In the diagram, S = Stop Lamp, R = Running Light, T = Turn signal, BU = Back-up Lights.**

These authors argued that no additional colors (beyond those used on current systems) were necessary for this design and that no new colors should be considered for future designs. The report also generated several useful design guidelines for rear-signaling systems; these are listed in the design guideline table in a separate section of this report.



Coleman (1967) conducted a study that evaluated the costs and benefits of changing over from one rear-lighting system to another. His conclusions were that used cars were the biggest hindrance to a complete vehicle population changeover. The largest costs and schedule impacts would be felt in the design of retrofit systems rather than in new car systems. Retrofit systems should take advantage of the existing harnesses which would need to work around power constraints. For new cars, the decision and standards formulation would not be a trivial matter, and conflicts would occur more often with vehicle styling rather than with lighting system effectiveness.

Coleman estimated that a complete changeover would take a total of seven years maximum (3-5 minimum). Note that the changeover period would likely be longer today, because vehicles tend to remain in use for more years than was true in the past. Designers must consider the trade-offs between a simple, inexpensive, nominally effective system versus a complex, expensive, very effective system.

Although a direct cost to the owner would be likely with the redesign of rear-lighting systems, the overall cost would be negative (Coleman, 1967). The monetary benefits include reduced insurance losses, reduced insurance premiums due to fewer crashes, reduced government cost for crash clean-up, reduced injury and fatality losses, and increased vehicle value. The negative financial aspects of a new lighting system would include increased initial vehicle cost, increased maintenance costs, increased insurance cost due to cost of repair, increased government cost due to changeover implementation, and loss due to vehicle repair downtime.

Mortimer and various colleagues conducted a large body of research into vehicle signaling in the late 1960s and through the 1970s. Mortimer (1969) found that the then-current rear-lighting system performed more poorly than did each of seven experimental systems. The arousal property of signals was found to be directly proportional to the number of lamps used. Separation of lamps by function and color coding of signals were also found to significantly improve performance. The most effective systems were those in which taillights, turn signals, and stop signals were represented by separate lamps, and Mortimer predicted significant gains in driver performance with use of these experimental light coding techniques. In a later comprehensive report on rear-signaling research, Mortimer (1970) reached the following conclusions:

- Separation of lamps by color and function is effective. Presence lamps should be green-blue, turn lamps amber, and stop lamps red. The stop lamps should definitely be functionally separated from other vehicle signals, and it would also be desirable to separate presence and turn signals (note that even today, stop signals are not required to be separated from turn or presence signals in either location or color).
- Improvement in driver sensitivity to closing rate was found with four presence lamps, two high mounted and two conventionally mounted.
- Signals should not be given on each release of the accelerator, and such releases are not reliable predictors of subsequent brake use. In only 34% of cases were accelerator releases followed by brake application. This means that there will be a large number of

false alarms for any signal which indicates accelerator release as an early warning signal for possible brake application. In only 14% of these cases was the brake applied within 0.5 seconds of the accelerator release (overall, in only 4.8% of cases was an accelerator release followed by a brake application within 0.5 seconds). A coasting signal would be undesirable, for the above reasons, and because such signals would typically be presented for short periods of time (1 to 2 seconds). Overall, not more than 7% of times would a coasting signal be considered as an early warning of impending braking. There are rare occasions when a long coasting period will be detected late by following drivers. A signal might be warranted for the case in which the driver is coasting for an extended period of time (e.g., five seconds or more). The stop signal could be activated whenever this situation occurs.

- Signals need to be perceived by following drivers. Signals with a high arousal capability would have low driver detection times and would be detected on most occasions on which they are shown. There is a benefit to be gained from high absolute intensities and from high signal/presence light intensity ratios.
- Coding of signals by lamp shape or lamp size/area will not provide powerful cues, since these types of coding will be difficult to perceive at the distances involved in driving (whereas color coding, intensity coding, and flash coding have been shown to be detectable at these distances).
- Night intensity should be lower than day intensity.
- An intensity override switch should be provided to allow daytime signal intensities to be used in poor atmospheric conditions (such as fog).
- Final recommendations for rear stop signals:
  - Should be red in color.
  - Not combined with any other signal.
  - Separated a minimum edge-to-edge distance of 5.0 inches from presence lamps.
  - From 15-30 inches in vertical position from the ground.
  - Inboard of the turn signals.
  - As far outboard as possible.
  - One lamp on each side.
  - Dual intensity for day and night, with an override switch for poor atmospheric conditions.
  - Activated when the accelerator is fully released for five seconds or longer.

Mortimer, Domas, and Moore (1974) performed simulator studies to assess the effects of rear-lighting system malfunctions. They found that the use of multiple lamp, redundant rear-lighting systems resulted in fewer errors of identification when one or more bulbs were not lit than the then-current single bulb/side system, although the differences were generally small.

In a later report, Mortimer (1979) described the first phase of a study meant to determine whether deceleration signals provide any benefit over the then current brake light systems, and if

so, to determine which aspects of the signal are responsible for the benefit. This report described seven tasks which were completed in pursuit of this goal. The first task was a review of prior research on deceleration signals, culminating with a thorough description of the Voevodsky (1974) experiment using a fleet of taxi-cabs in San Francisco. Voevodsky showed an ~60% reduction in rear-end crashes as a result of the “Cyberlite” system, which consisted of a yellow light located in the rear center of the vehicle, just above the rear bumper. The light flashed at various rates according to the deceleration rate, ranging from 1Hz at 0.0g to 7.5Hz at 0.5g. Mortimer points out that the greatest reduction in crash rates was for a very high intensity version of the Cyberlite (three intensities were used, 600, 1,200, and 1,800 cd). Mortimer then pointed out that the results of the Voevodsky experiment did not make clear the possible reasons for the reduction in crash rates (the color, position, flash rate, or intensity of the light, or perhaps even the mere presence of a third light). Thus the purpose of the Mortimer investigation was to tease out the relevant factors, and then produce and field test a set of optimized deceleration signals.

The second task involved selection of deceleration displays for preliminary evaluation. By varying flash rate, intensity, number of lights, and combinations of these, a list of 41 displays was generated. The third task was the scaling of the flash rate for a deceleration signal. Preliminary results were obtained using a just-noticeable difference experiment and a magnitude estimation experiment. These results were then used to run an experiment of absolute judgment. The results showed that no more than three frequencies can be expected to be discriminable on an absolute judgment basis over a range of frequencies of about 1-9 Hz. The three discrete frequencies suggested by the results of all three experiments would be approximately 1.0, 2.5, and 6.5 Hz. Based on these results, Mortimer concluded that the use of more than three flash rates, or the use of a continuously varying flash rate, would not provide any additional information to the following drivers than would the use of these three frequencies.

Task 4 involved the subjective evaluation of the deceleration signals. Two experiments were run. The first experiment was run in the daytime. Four subjects rode in a car following the lead car, which was outfitted with programmable rear lighting allowing 21 deceleration signals to be displayed on the rear of the lead car, in addition to the normal brake lights. Subjects rated their perception of each signal’s effectiveness during the course of this on-road experiment. It should be noted that one of the signals was effectively a CHMSL, and provided no information about deceleration. Results showed that varying both the number of lamps and the flash rate was thought by the subjects to provide the most information about deceleration, with number coding being the preferred coding scheme (number coding refers to using a larger number of lamps to represent greater deceleration). Intensity coding was also perceived positively when very high intensities were used. The results led to the conclusion that not more than two levels of deceleration should be coded.

The second experiment of Task 4 was similar to the first, except that it was run both in the day and at night, 26 deceleration signals were tested (again, with a CHMSL as one of the signals), and the dependent measures were the subjects’ rating of: 1) the attention-getting quality of the signal; 2) the information provided as to the magnitude of deceleration; and 3) how distinguishable the signal was from other signals. A number of results were obtained:

- A combination of color and flash coding was rated the highest.

- Number coding alone was the next most effective coding scheme.
- For single lamp systems, combined flash and intensity coding was most effective, followed by flash coding alone.
- High intensity systems were rated higher than low intensity systems, and there were fewer complaints than expected regarding glare from the high intensity systems.
- Intensity coding alone was not judged to be an effective coding scheme.
- The CHMSL-type system (remember that this experiment was run during the pre-CHMSL era) did not provide an increase in deceleration signal effectiveness, but it made the brake signal more distinguishable.
- Day and night rankings of the systems were similar (the nighttime signals were reduced in intensity by 30% using filters). The systems were perceived as more effective at night.

Based on the results of the Task 4 experiments, six configurations were chosen for more extensive on-road testing. One was the conventional rear-lighting system, one was the CHMSL, and the other four were single lamp systems using a combination of flashing and steady burning lamps activated at different deceleration forces (criterion levels were 0.1g, 0.2g, and 0.3g). Two of the systems used two different flash rates (3Hz and 5Hz) while one only flashed at 3Hz above 0.2g, and the other used a linearly increasing flash rate depending on deceleration. Note that although the earlier tasks had shown that number coding was the most effective coding mechanism, it was decided to drop number coding from consideration due to cost and power supply constraints. Thus all systems tested in Task 4 and beyond were single lamp systems, in the center high-mounted position, and red in color.

The fifth task was a car-following and subjective evaluation of braking deceleration magnitude, evaluating the six signals selected in Task 4. Fourteen subjects were used in on-road tests in daylight. The independent variables included lighting condition (seven levels, the six described above as well as a no-signal condition) and deceleration level of the lead vehicle (0.15g, 0.25g, and 0.35g). There were numerous dependent variables, including objective measures such as brake reaction time and maximum reduction in headway, as well as subjective measures such as impressions of brightness, distraction potential, and alerting potential. The findings showed that there were only minor differences in the manner in which drivers responded to the deceleration levels of the lead vehicle with the different signaling configurations. The study also demonstrated that conventional brake lamps provide a significant advantage over no signals (this hypothesis had not been tested before this study). The study also showed that drivers were not aided to any great degree by any of the deceleration signals based on the measures of driver performance used.

Task 6 was the selection of five configurations for full-scale field testing based on the results of all tasks completed up to that point. The systems selected were as follows: 1) the standard rear-lighting system (pre-CHMSL); 2) the CHMSL (though it was not called that at this time); 3) a CHMSL that would flash at 2.5Hz during braking (the basic flashing CHMSL suggested so often over the years); 4) a flash coded CHMSL with three flash rates that would burn steadily from

0.0g to 0.1g; and 5) a flash coded CHMSL with four flash rates that would also flash at 0.0g to 0.1g. Through paired comparisons of the lights, this combination of signals addressed most of the unanswered questions arising from the Voevodsky fleet test: the effect of an added brake lamp, the effect of a flashing an added brake lamp, and the effect of flash coding the third lamp based on deceleration level.

The seventh and final task for this phase of the project was an analysis of the braking deceleration distributions for urban environments (motor pool and taxi cabs). For this task, a number of taxi cabs and motor pool cars operating in urban environments were fitted with deceleration detectors which were designed to count the number of decelerations within various ranges. There were two purposes for this study: to see whether these vehicles were appropriate for fleet testing, and to test the devices that would be used to activate the deceleration coded lamps in fleet testing. Based on the distribution of decelerations, the taxi cabs and motor pool vehicles were deemed appropriate for fleet testing, and the devices were found to work as intended, with periodic calibration.

In a follow-up report, Mortimer (1981) described the procedures and results for the fleet testing of the lamps selected in Mortimer (1979). For unspecified reasons, the five light configurations chosen in Task 6 of the first report were reduced to three for the fleet testing: 1) a flashing CHMSL (2.5Hz whenever the brakes were applied); 2) a deceleration dependent flash coded signal with four levels of flashing; and 3) a steady burning CHMSL. Even though this was a smaller set of signals than proposed in the previous report, through paired comparisons of the lights, this combination of signals addressed most of the unanswered questions arising from the Voevodsky fleet test: the effect of an added brake lamp, the effect of a flashing an added brake lamp, and the effect of flash coding the third lamp based on deceleration level. The lights were mounted on over 600 taxicabs in San Francisco and Sacramento and tested for about one year, during which time almost 41 million miles were accumulated by the vehicles. There was no control group of cabs (the cabs equipped with the new signals were not compared to cabs with ordinary brake lights). Thus the purpose of the study was simply to compare these three experimental brake signals.

Results showed that the CHMSL had a lower crash rate (4.4 rear end crashes per million miles driven), followed by the flashing CHMSL (4.9 per million miles), and the deceleration coded lamp (5.2 per million miles). These differences did not reach statistical significance. Most vehicles (78%) were stopped in traffic when rear-ended, while 22% were stopping, either slowly or quickly. Only a small subset of the crashes occurred when the cab was decelerating quickly. Mortimer concluded that a stopped or slowly moving vehicle signal would be more effective than a deceleration signal for preventing rear-end crashes. Mortimer also concluded that most of the reduction in rear-end crashes reported by Voevodsky was due to the mere presence of a third brake lamp, regardless of color, flashing, mounting position, or intensity.

Attwood (1976) performed a high-level summary of rear-lighting research in the late 1960s and early 1970s, focusing on those studies that examined the use of color and functional separation. Functional separation refers to having the brake lights separated from the turn signal and presence lamps in order that the brake lights are not confused with or overridden by the other

signals. Attwood's report is basically a literature review of many of the same reports summarized here.

### Rear-signaling Efforts for Commercial Trucks and Transit Buses

Recent government efforts have focused on improving the rear-signaling for transit buses under a Federal Transit Administration IVI program. These projects are still in their early phases, and also include efforts to reduce side and frontal impacts to transit buses. Some of the efforts focus on rear-lighting, while others focus on in-vehicle collision avoidance warning systems. The work is being carried out by various research organizations around the country. Although much of the work is still in the preliminary phases and is not yet published, the work that has been published to date will be described briefly here.

California Partners for Advanced Transit and Highways (California PATH) and UC Berkeley are conducting work that will lead to algorithms for frontal collision avoidance warning systems (Chan, Zhou, Wang, and Zhang, 2001). Carnegie Mellon University is devoting effort to developing side collision warning systems for transit buses (McNeil, Thorpe, and Mertz, 2000; Mertz, McNeil, and Thorpe, 2000; and Duggins, McNeil, Mertz, Thorpe, and Yata, 2001). This work has progressed to the point of problem description and the development of functional goals. Foster-Miller is developing the driver/vehicle interface for a longitudinal and lateral collision avoidance system (Everson, 2000; Reinach and Everson, 2001). The transit bus research most closely aligned with the current project is being performed by Veridian, which is developing a bus-mounted light bar to warn of an imminent rear-end collision (Cohn, 2001). This light bar reportedly uses amber lenses and has several operational modes such as flashing and sequential illumination. Knowledge of the Veridian work is limited to an internal memo provided by the project sponsor, and no published reports were found in the literature.

One effort towards improving the conspicuity of commercial truck trailers also deserves mention. Heavy trailers manufactured after December 1, 1993 were required to be equipped with red and white retroreflective tape or reflex reflectors. As study by Morgan (2001) showed these passive markings to be highly effective at preventing side and rear impact crashes in dark conditions (reductions in the range of 29-41% were reported). The tape apparently alerts other drivers to the presence, size, and shape of the trailer, thus providing drivers with additional time to react to the trailer. This study demonstrates that a relatively simple design change which provides enhanced attention-getting properties has the potential to significantly reduce crashes.

### Design Guidelines

Several of the research efforts conducted in the 1960s began with the development of guidelines for the design of rear-signaling systems. The design guidelines developed were similar for most of these studies; however, each study also contributed unique guidelines. Table 10 provides a synopsis of these guidelines with details about which studies were in agreement with each guideline. (Note that the Moore and Rumar 1999 report is also included in Table 10, as it also included a set of design guidelines.)

**Table 10. Design guidelines from five key design and evaluation studies of rear-signaling systems. (\* indicates agreement with guideline. A blank indicates either disagreement or the guideline was not evaluated)**

<b>DESIGN GUIDELINE:</b>	<b>Case et al. (1968)</b>	<b>Nickerson et al. (1968)</b>	<b>Projector, Cook, &amp; Peterson (1969)</b>	<b>Finch &amp; Horning (1968)</b>	<b>Moore &amp; Rumar (1999)</b>
Standardization is imperative.	*		*		
Redundancy is desirable.	*	*	*	*	*
Signals must not be ambiguous.	*	*	*		
Natural sources of information should be preserved.	*	*	*		
Directional signals should be different color than brake signals.	*				
Color coding should be used.		*	*		
Red should be used for braking.	*	*	*		
Signals must be large, bold, and simple.	*	*			
Other coding dimensions (position, number, intensity, flash rate, shape, area) should be used.		*	*		
Signals must be reliable.	*				*
Signals must have a favorable signal-to-noise ratio/two levels of intensity.	*	*	*	*	*
Signals must observe a hierarchy of criticality.	*				
Public's preconditioning and risk compensation must be taken into account.	*	*			
Braking and stopped vehicle signals should be different.					*
International harmonization of regulations should be attempted.					*
Eliminate license plate lamps.					*
Reduce exposure to dirt and corrosion.					*
Eliminate drivers' misuse of signals.					*
Teach proper car following behavior.					*
Turn signals should be visible from the side.		*	*		
System must be economical to produce.		*			
Running lights should be used in the daytime.			*		
Critical signals should be high on the vehicle.			*		
Rear-signal system should provide both vertical and horizontal dimensions for frame of reference regarding distance information.			*		
Predictive information should be provided without ambiguity.			*		
Reflective materials should be used to ensure conspicuity.			*		





Several of these design guidelines were presented in more than one of the reports, and many of them overlap slightly. Generally speaking, most authors agreed that rear-signals should be redundantly coded and unambiguous, with the natural information sources preserved. The brake light should remain red in color and the entire system should maintain a favorable signal-to-noise ratio (meaning that the intensity of the lamps should change with the ambient lighting conditions). In addition, Mortimer (1970) provided the following list of guidelines, which do not overlap significantly with those presented in Table 10:

- The redundancy principle should be used in the coding of signal lights.
- Red should be used for braking only.
- The case for green as a taillight color is strong.
- The rear-lighting system should have multi-intensity capability.
- There should be some relative standardization of the locations of lamps carrying specific functions.
- The early warning light principle requires further investigation.
- Velocity and deceleration information appears to be useful for following drivers.

#### Long-term Effectiveness of the Center High-Mounted Stop Lamp

Mortimer wrote one critique of the center high-mounted stop lamp (CHMSL) in 1986 when the device was first implemented, and another in 1997 after the device had been in use for approximately 10 years (Mortimer, 1986; 1997). His initial criticism of the device was that 80% of all rear-end collisions involve a stopped vehicle, and the CHMSL is a third brake lamp rather than a stopped vehicle signal. Mortimer argued that a stopped vehicle lamp or signal was needed more than a third brake lamp. He also suggested that drivers may brake inappropriately when they observe the CHMSL activated in a vehicle two or three places ahead in a line of traffic. In his 1997 critique, he modified that argument, since observing a CHMSL down a long line of cars has not proven to cause inappropriate brake activations (Mortimer, 1997). However, he then argued that drivers continue to need information on rate of closure or relative velocity rather than a third brake light.

In another article, Mortimer (1993) discussed the theoretical underpinnings for the CHMSL, and concluded that there is no scientific evidence to back up any of the theories. He argued that this is the reason that the CHMSL has not lived up to its early promise of a 50% reduction in rear-end crashes. He claimed that the true benefit is about 3.5%, which is about the level of effectiveness to be expected given the theories involved.

In a more recent article, Mortimer (1999) explored some of the questionable assumptions behind the mandate for CHMSLs, including:

- Mounting height:
  - There was no research showing that the high position would be beneficial.
  - There was no evidence that the ability to see brake lights through intervening vehicles impacts braking behavior:
    - Drivers do not necessarily brake when they see brake lights ahead.
    - The ability to see through intervening cars is limited.
  - There are ambiguous results in research on the response time of drivers exposed to high mounted brake lights versus standard (pre-1986) brake lights.
  - At the distances involved in typical driving, having the brake light mounted high or low means that it will still be within the 2° field of view of the fovea.
- Intensity:
  - The intensity that was chosen is high enough to cause glare, and was selected without good experimental basis. The intensity is higher than that recommended by SAE.

Some of the positive aspects of the CHMSL were also noted:

- Separation in location from other brake lamps reduces confusion.
- The lamp is redundant to other brake lamps.
- The CHMSL results in a triangular configuration that can only mean braking.
- The function of the CHMSL is separate from any other signal on the vehicle (separation of function).
- The intensity should make CHMSLs readily noticeable (but will also cause glare problems).

Kahane and Hertz (1998) conducted a study to systematically determine the long-term effectiveness of CHMSLs. The main finding pertinent to the present study is that, generally speaking, the CHMSL is more effective for simpler crash scenes. In complex crash scenes where there are numerous lights and vehicles, the CHMSL is less effective. CHMSLs are more effective in the daytime and in rural areas. They are more effective on wet roads than on dry or snowy roads. The overall effectiveness of CHMSLs has reached a plateau of approximately a 4.3% reduction in rear-end crashes as compared to pre-CHMSL figures. These findings may suggest that new lighting technologies may be most effective in less complex crash scenes, and that additions or changes to the current rear-signaling system may be less effective in complex situations.

#### NHTSA Statement of Policy for New Signaling Ideas

NHTSA is currently working with the United Nations' Meeting of Experts on Lighting to develop a process for evaluating new lighting concepts for signal lamps on vehicles. Until

recommendations from this work are complete, NHTSA has adopted the following policy (Federal Register, 1998) for evaluating new vehicle signal lamp concepts. When the agency is asked to evaluate a new signal lighting idea, NHTSA will ask the following two questions:

1. Does the new signal lighting idea require a change in the standardized operation or appearance of a required lamp or piece of lighting equipment?
  - a. If NHTSA determines the answer is NO, then does the new signal lighting idea impair the effectiveness of required lamps or lighting equipment?
    - i. If NHTSA determines the answer is YES, the new signal lighting idea is expressly prohibited by the lighting standard.
    - ii. If NHTSA determines the answer is NO, the new lighting signal idea may be installed on vehicles.
  - b. If NHTSA determines the answer is YES, the agency will proceed to Part 2 of this evaluation.
  
2. The current standardized approach for signal lighting has positive safety benefits by virtue of its broad public and international acceptance. Does the request to alter the current standardized approach for signal lighting present data purporting to show positive safety benefits from the new signal idea?
  - a. If no data are provided, NHTSA will not treat the request as a petition for rulemaking. The request will be forwarded to a public docket that will collect information describing all proposed new signal lighting ideas and systems. The docket will be available for review by NHTSA and others who may wish to plan future research based on the ideas and inventions collected in the docket.
  - b. If data are provided, NHTSA will treat the request as a petition for rulemaking. NHTSA will evaluate the data to determine if they show persuasive evidence of a positive safety impact.
    - i. If NO determination of positive safety can be made, NHTSA will not change its regulations to permit the new signal lighting idea, because that would negatively affect standardization of the signal lighting.
    - ii. If YES, a determination of positive safety can be made. NHTSA will propose to amend its lighting standard to either permit or require the new signal lighting idea.

NHTSA has received many new ideas for stop lamp improvements over the last 30 years. Many of these ideas involve altering the current stop lamp configuration which NHTSA is reluctant to do given its standard unambiguous signal. NHTSA does acknowledge that it is *possible* to improve upon the current configuration but only if there is scientific evidence to demonstrate that such a change would yield net safety benefits.

This policy has been applied to four new signaling concepts since its implementation in 1996. The first concept was ABWS (Advance Brake Warning System) which was developed by Baran Advanced Technologies, Ltd. of Israel. This system initiates the activation of the brake lamps when the driver's foot suddenly releases the accelerator. This type of device, as defined by NHTSA's policy, would require a change in the standardized operation of signaling lamps, and the net safety improvement for this device is questionable given the method of data collection and analysis. (See Federal Register/Vol. 63, No. 231/Wednesday, November 4, 1998/Rules and Regulations for more information.)

Flashing CHMSLs to warn following drivers of hard braking and flashing CHMSLs to warn of a stopped vehicle would also require a change in the standardized operation of required lamps. The scientific literature has not shown any significant improvement in drivers' detection of flashing lamps versus steady-burning lamps. The flashing lamps have been reserved for turn signals and hazard lamps in the current rear-lighting configuration. Without additional scientific research showing that a flashing lamp will be detected significantly faster than a steady-burning lamp, NHTSA will not consider altering the standard.

Front brake lamps to alert oncoming vehicles that the subject vehicle is braking would not require a change in standardized operation of required lamps. The only issue for these front brake lamps is whether they would negatively impact the effectiveness of the required front lighting. Provided that there is research to adequately prove that the front brake lamps were designed so as not to conflict or negatively impact the front lighting, then NHTSA's lighting standard already permits these front 'brake' lamps to be installed.

### **Rear-lighting Configurations and Characteristics**

This section of the literature review covers research articles and technical reports that investigated specific rear-lighting configurations, specific characteristics of rear-lighting systems, and human performance characteristics that coincide with the perception of rear-lighting systems.

#### Rear-Lighting Configurations

Rockwell and Banasik (1968) conducted an applied study that compared four different experimental rear-lighting systems to a conventional system. The experimental systems encompassed four levels of information presentation. These lighting configurations, tri-light, acceleration, advanced headway and relative velocity, and fusion light system, are described in Table 11.

**Table 11. Rear-Lighting Systems Developed and Evaluated by Rockwell and Banasik (1968).**

<b>Lighting Configuration:</b>	<b>Lighting Configuration Description:</b>
Tri-Light	A three-color system for presenting pedal information. A red light would illuminate for braking, an amber light for no pedal activation, and a green light for accelerator activation.
Acceleration	This is also a three-color system with slightly different meanings: red would indicate rapid deceleration, amber would indicate mild deceleration, and green would indicate acceleration.
Advanced headway and relative velocity (H-RV)	This system would use colored taillights to indicate headway and relative velocity information. Green would mean 'too far back, move up a little'; green plus amber would indicate 'perfect following distance'; amber would indicate 'just a little too close'; red plus amber would indicate 'too close'; and red would mean 'much too close.'
Fusion	This is a system based on the principle of light fusion in which lights can be spatially separated in such a way that, when viewed from a certain distance, they would appear to be a single light.

These lighting configurations were designed based on the principle of guided evolution. Each configuration would be introduced at a point in time after the previous system had been introduced and the public had adjusted to it. Each system uses information from the previous system so that the public can adjust to changes in small stages before the next improvement is introduced. Another benefit to this approach is that each new system can incorporate the latest technology as it is implemented rather than having to rely on rigid specifications.

Rockwell and Banasik also evaluated information transfer with each of these systems. They investigated the general principles of what information should be presented to the following driver and how effective the following driver is at processing this information. This evaluation did not lead to any design guidelines but, rather, to the general principles for rear-lighting research presented below:

- It is important to use a live highway environment for testing.
- Rapid and natural understanding of the meaning of new rear-lighting systems is essential (using cultural stereotypes, for example).
- Redundancy of coding is essential.
- The complexity of the problem means that the complex interaction of the human in the visual environment and under various signal configurations has to be carefully investigated.

- There is a need for research on the psychophysics of driving. This refers to research investigating what information the driver perceives well and what information the driver needs help in perceiving.

The Rockwell and Banasik study was a very ambitious three-phase study in terms of the number of systems considered, live highway testing, driving maneuvers, and the number of dependent variables. While their effort was impressive, their ability to maintain experimental rigor was compromised. Only six subjects were used in the first two phases of the study (an extremely small sample size). The authors were attempting to conduct this study in a limited time frame and much of that time was spent developing systems and designing an elaborate research protocol. The results suggest that the advanced headway and relative velocity systems were better in nearly every regard, but the small sample size restricts the generalization of their findings.

Rutley and Mace (1969) also conducted a study in the 1960s in which they proposed and tested a different brake light display. This research was conducted in the United Kingdom and provides information on European rear-lighting research. Rutley and Mace compared three different systems: no brake lights, normal brake lights, and a row of multiple brake lights that presented deceleration information. The row of brake lights indicated deceleration by lighting up from the center to the outside as deceleration increased. The experimental results suggested that both types of brake lights decreased reaction time as compared to the no brake light condition. Analysis of the full data array led to the conclusion that the same benefit would have been gained for a system where the brake lights come on as soon as the accelerator is released.

To test this conclusion, the authors performed a second experiment in which they replaced the no-brake light condition with an accelerator light condition. Both the accelerator light and multiple brake light systems produced faster reaction times than the normal brake light alone, but the two new systems did not differ from one another statistically. The authors concluded by proposing a two-level brake light system in which low levels of deceleration would be presented by one level of lights and hard deceleration would be presented by a second level of lights.

To improve driver reaction time, Flannagan and Sivak (1989) invented a device that preheats the filament of the brake lamp and supplies an over-voltage when the lamp is activated. This preheating mechanism allows the brake lamp to illuminate more quickly. The authors conducted an evaluation showing that this mechanism could result in a 115 ms reduction in reaction time, based on simulated tasks. The authors received a patent for this device in 1988.

In the same vein of research, Olson (date unknown) evaluated the Advance Braking Light Device which senses the rate at which the accelerator is released. When the accelerator is released at a rate greater than or equal to a predetermined minimum, the device would activate the brake lights for one second. If the driver then braked, the brake lights would stay on with the activation of the brakes. If the driver did not brake, the brake lights would turn off after the designated one-second interval. This device would allow the brake lights to be illuminated 200-300 ms sooner than with the current system. However, Mortimer (1970) conducted research showing that in only 4.8% of cases is an accelerator release followed by a brake application within 0.5 seconds. Thus the Advance Braking Light Device would be of limited practicality.

Another system, developed by a private citizen,<sup>1</sup> would use three lighting configurations. A green light would be illuminated when the accelerator is activated, a yellow light would be illuminated when neither the accelerator nor the brake is activated, and a red light would be illuminated when the brake pedal is depressed. This lighting configuration is similar to several that were developed and evaluated in the 1960s.

The described lighting configurations all are different systems with a single goal: improving the following driver's reaction time to brake lights. In some cases this is attempted by use of a device intended to capture the following driver's attention more readily. Some innovators advocate speeding up the bulb activation time. Others attempt to decrease the following driver's reaction time by making use of the 200-300 ms time that it takes for a driver to move a foot from the accelerator to the brake. While some simulator studies show improvement in reaction time using these methods, on-road research is needed to determine if these concepts will actually improve braking reaction time. The only U.S. research study involving an on-road technique used a very small sample of subjects, which casts some concern on the generalizability of those findings.

#### Lighting Characteristics

*Lighting Intensity.* Mortimer (1970) conducted a study of the required intensity levels for red stop lamps to be viewed at 75 feet. The recommended values are shown in Table 12, and take into account the trade-off between the need for an identifiable daytime signal and a non-glare nighttime signal.

**Table 12. Dual intensity recommendations for red stop lamps viewed at 75 feet (from Mortimer, 1970).**

Condition	Night		Day	
	Minimum	Maximum	Minimum	Maximum
Lamp size				
12.6 square inches	80 cd	190 cd	300 cd	2,300 cd
18.0 square inches	95 cd	230 cd	380 cd	2,800 cd

Mortimer, Moore, Jorgeson, and Thomas (1973) conducted an intensive survey of all car and truck signaling and marking research, and also conducted several studies related to rear signaling. Their findings relevant to this study were that signals should become identifiable at distances up to 2,000 feet. They recommended the use of dual intensity signal to solve the conflict between the need for signal bright enough to be identified in daytime, but not so bright as to cause discomfort glare at night. Mortimer et al. recommended a minimum daytime intensity of 300 candelas and a maximum nighttime intensity of 190 candelas (for 12.6 in<sup>2</sup> red stop lamps which can be identified correctly 85% of the time at 2,000 feet, yet do not cause discomfort glare to more than 15% of people at 75 feet).

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<sup>1</sup> From this point forward, authors who presented ideas to NHTSA as private citizens, and whose ideas were not subsequently patented, will be referred to as *private citizen* or *innovator*. The term *inventor* will be reserved for those whose idea received a patent, and they will be identified by name in this report.

In a finding with implications for the current study, Mortimer et al. (1973) also found that flashing lamps cause less discomfort glare than steady-burning lamps of the same intensity. This finding, while surprising on the surface, makes sense if discomfort glare results from the sum of light intensity received at the eye over a set amount of time. Thus, because a flashing light is not continuously on, the eye receives less overall light. However, the annoyance potential of flashing lights may outweigh this finding with regard to discomfort glare.

Bhise (1981) performed an SAE sponsored study at the Ford Dearborn Proving Grounds investigating the conspicuity of red rear-signaling lights while varying the luminance intensity and area of the lamps. The results of the four experiments conducted as part of this study are presented below:

- Experiment One. The author wanted to determine tail-lamp detectability during daytime viewing conditions. Three lighting intensities (40, 60, and 80 candela) and three tail-lamp sizes (4, 8, and 12 square inches) were used. Detectability increased as lighting intensity increased but there was no measurable effect for the size of the tail lamp.
- Experiment Two. This study investigated the identification of tail lamps versus stop lamps. Seven lamp intensities (10, 20, 30, 40, 60, 80, and 100 cd) and two lamp sizes (4 and 8 in<sup>2</sup>) were used as independent variables in this study. Lamps with lighting intensities greater than 20 cd were identified as tail lamps more than 80% of the time, while lamps with lighting intensities greater than 60 cd were identified as stop lamps more than 90% of the time. Once again there was no effect for lamp size.
- Experiment Three. The conspicuity of lighting signals in daylight driving conditions was investigated in the third experiment. Four intensity levels (40, 60, 80, and 100 cd) and four lamp sizes (4, 6, 8, and 12 in<sup>2</sup>) were used as independent variables. The results of this study indicated that daytime conspicuity increased as signal intensity increased, but that there was no effect for lamp size.
- Experiment Four. Experiment Three was repeated except that nighttime driving conditions were investigated. The same levels of independent variables were used and the results were identical. Conspicuity increased as signal intensity increased, but there was no measurable effect for signal lamp size.

These four studies suggest that conspicuity of rear signals will improve with lamp intensity in both daytime and nighttime viewing conditions; however, lamp size, as it varies from 4 to 12 in<sup>2</sup>, has no measurable effect on the detectability or conspicuity of the signal.

A similar study was performed for the U.S. Department of Transportation to investigate photometric properties of lights and driver detection of these lights (Sivak, Flannagan, Olson, Bender, & Conn, 1986). Given the results of this research, the authors suggested that luminance intensity should be retained as the relevant photometric parameter for brake lamps. They also suggested that 80 cd should be retained as the minimum luminance intensity for brake lamps.

Earlier, Cook (1969) conducted a study investigating the intensity of rear-signaling lights in both daytime and nighttime driving conditions. The results suggested that a maximum intensity of



300 cd of red light be allowed for nighttime driving. Taillight intensities should remain between 10 and 30 cd, while brake and turn signal light intensities should remain near 100 to 300 cd. The author suggested that specularly reflecting surfaces be prohibited in the immediate surround of signal lights (the suggested intensity ratings were all based on having no specularly reflecting materials near the rear signal lights). This research investigated the issues of glare, variable intensity lights, and visibility of lights in bright sunshine.

Sayer, Flannagan, and Sivak (1995) performed a study prompted by the recent trend towards incorporating long, narrow CHMSLs into automobile spoilers and trunk lids. At present, U.S. regulations require that stop lamps and CHMSLs meet certain area (minimum only) and intensity requirements (both maximum and minimum). However, there is no regulation for aspect ratio (ratio of height to width) for these lamps. There is some question of whether these long, narrow CHMSL have an adverse impact on safety, even though they meet the requirements for area and intensity. Subjects were asked to respond to the presentation of stop lamps while performing a tracking task similar to driving. Stop lights were presented using slide projectors with the light output subjected to various filters to obtain the proper color and uniform luminance.

Two levels of intensity (35cd and 150cd), two levels of area (50 cm<sup>2</sup> and 150 cm<sup>2</sup>), and three aspect ratios (1:1, 1:6, and 1:67) were investigated. The area and intensity levels were chosen as representative of stop lamps and CHMSLs, while the 1:6 aspect ratio is typical of a traditional rectangular CHMSL, and the 1:67 ratio approximates the condition of a narrow CHMSL extending across the width of a typical vehicle. There were significant main effects on reaction time for intensity (shorter reaction time for higher intensity lamps) and aspect ratio (with a significantly longer reaction time for the high aspect ratio condition, similar to the long, narrow CHMSL). The interaction between intensity and aspect ratio was also significant (for low intensity stimuli, there were large differences in reaction time among the three aspect ratios, while for the high intensity signals, the reaction times were quite similar for the three aspect ratios). The authors conclude with a recommendation to study these relationships in greater detail, with the goal of regulating aspect ratio if warranted by further research results.

In a follow-up study, Sayer, Mefford, Flannagan, and Sivak (1996) conducted further evaluations of the long, narrow CHMSL. In the second study, they investigated the effects of context (whether or not the stop lamps were also presented), aspect ratio, intensity, and ambient illumination (simulated day and night) on reaction time to a CHMSL. The results were similar to those found in the earlier study. Reaction times were significantly longer for the low intensity CHMSL, for the large aspect ratio CHMSL, and when the CHMSL was shown without low-mounted stop lamps. The combination of low intensity and high aspect ratio was found to be especially troublesome.

The research results summarized here generally support the current regulations established by NHTSA for the intensities of stop lamps, turn signals, and running lights (the current U.S. standards for rear lamp luminance are summarized in Table 13). However, research scientists have made a strong case for dual intensity rear-signaling systems since the late 1960s, and this recommendation has yet to be adopted. The switching technology for dual or variable intensity lighting has become commonplace among inexpensive electronic devices, and it seems strange

that it has not yet been applied to the rear-signaling systems of automobiles. Another factor not addressed in current standards is the effect of long, narrow CHMSLs on reaction time.

**Table 13. National Highway Traffic Safety Administration, DOT: Minimum and Maximum Allowable Candlepower Values (Adapted from Federal Motor Vehicle Safety Standard: 571.108 Standards on Lamps, Reflective Devices, and Associated Equipment).**

Lamp	Lighted Sections		
	1	2	3
Stop	80/300	95/360	110/420
Tail *	2/18	3.5/20	5.0/25
Parking **	4.0/125	--	--
Red turn signal	80/300	95/360	110/420
Yellow turn signal (rear)	130/750	150/900	175/1050
Yellow turn signal (front)	200/-	240/-	275/-
Yellow turn signal (front) ***	500/-	600/-	685/-

\* Maximum at H or above.

\*\* The maximum candlepower value of 125 applies to all test points at H or above. The maximum allowable candlepower value below H is 250.

\*\*\* Values apply when the optical axis (filament center) of the front turn signal is at a spacing less than 4 inches (10 cm) from the lighted edge of the headlamp unit providing the lower beam, or from the lighted edge of any additional lamp installed as original equipment and which supplements the lower beam.

*Color Specificity.* There is research suggesting that reaction time decreases when a red signal is reserved strictly for brake lamps (i.e., other colors are used for tail lamps and turn signals). Cameron (1995) had subjects watch a rear-signaling system in which a red light was present when brakes were applied and an amber light was present at all other times. This static experiment was conducted to determine identification accuracy and reaction time to the proposed system as compared to a conventional rear-lighting system. Both identification errors and reaction time decreased when subjects were instructed to regard all red lights as brake lights. These results suggest that red presence lamps are not as effective as amber presence lamps, and that identification will increase and reaction time will decrease when red is reserved only for the brake lamps. Corroborating research for these results includes the study by Sivak, Flannagan, Olson, Bender, and Conn (1986), which found similar results when using green lights for running lights and red lights only for braking. Bullough, Boyce, Bierman, Conway, Huang, O'Rourke, Hunter, and Nakata (2000) also found that reaction time was fastest when a red light was presented and equally slower when green or yellow lights were presented (in the context of a traffic signal).

*Light Emitting Diode (LED), Incandescent, and Neon Lamps.* A recently published study compared the differences between LEDs and incandescent lights in daylight conditions (Bullough, Boyce, Bierman, Conway, Huang, O'Rourke, Hunter, & Nakata, 2000). The results suggest that there are no significant differences in mean reaction time, percentage of missed signals, color identification, subjective brightness, or conspicuity ratings between these two light sources.

A trade article (Keebler, 1993) announced that neon lighting would soon become available in vehicles. While neon lighting is not yet in widespread use in vehicles, the article suggested that the major advantage of neon is the fast rise time. Neon lights will illuminate in just 2 ms (standard incandescent lighting takes approximately 200 ms). The author calculated that this could mean an extra 24 feet of stopping distance in 60 mph traffic, although VTTI calculations show the true distance to be closer to 13 feet.

### Driver Characteristics

Many researchers have touted the value of focusing research efforts on identifying which visual information drivers perceive well and which information drivers tend to misperceive. This knowledge would allow designers to develop systems to assist drivers in their perception of information (Henderson, Sivak, Olson, & Elliot, 1983; Rockwell & Banasik, 1968).

*Perceptual Factors.* There are numerous perceptual processes by which humans can detect changes in relative velocity, inter-vehicle spacing, or relative headway. These processes can also interact in complex ways. In reading this section, keep in mind the following list from Hoffman (1968). Humans may be able to detect changes in relative velocity, inter-vehicle spacing, or relative headway:

- By a change in the size of the retinal image.
- By using information from the streaming of objects in the visual field to infer changes of speed or spacing.
- At short distances, by using binocular cues from retinal image size.
- In certain situations, by detecting changes in texture of the background.
- By detecting convergence of the parallel sides of the roadway with increasing distance.
- By detecting the changing position of the lead vehicle relative to the horizon with changes of spacing.

Mortimer (1972) found that the 50<sup>th</sup> percentile Weber's Law value for driving headway is approximately 0.12 (that is, drivers were just able to detect a reduction of 12% in headway as compared to the original headway). These experiments were conducted at initial headway distances of 40 to 320 feet. The visual cues used were various configurations of rear lighting (two, three, and four light configurations).

Colbourn, Brown, and Copeman (1978) investigated driver following behavior using a controlled test track. Drivers of varying levels of experience (inexperienced drivers with a mean of 1.6 years of driving, low experience drivers with a mean of 4.3 years of driving, and experienced drivers with a mean of 17.7 years of driving) were used in this experiment. Drivers were instructed to follow a lead vehicle at a comfortable distance and were also told whether the lead vehicle had a high probability of slowing down (driving through a urban, business district) or a low probability of slowing down (driving through a rural area). The lead vehicle traveled at one of three speeds: 48.3, 66.0, or 80.5 mph. The subject was not able to view any of the dashboard

controls on the vehicle, and was asked to safely follow the lead vehicle. Eight measures were taken of following distance using an in-vehicle display of headway. Only the experimenter was able to view the headway display.

The results of the study were inconclusive and did not support the two original hypotheses. Subjects' performance did, however, approximate the '2 second' rule of thumb suggested by a number of official sources for safe following distances. This is even more impressive since the drivers were not aware of their actual speed. They were only able to use their perceptual judgments of headway. Relative constancy of headway adoption extended across both instructed conditions of stopping may have occurred because the test track driving environment did not change. The subject was only supposed to drive *as if* they were in a urban environment. The experimenters did notice that subjects were anticipating that the lead vehicle was going to stop in the high probability conditions more than in the low probability conditions.

Given the results of this study, it appears that drivers are able to perceptually judge safe following distances in clear, dry weather. In view of the present results, risk perception and hazard recognition appear to be important factors. These factors have also been found to impact drivers' behavior in simulator studies and traffic flow research. It is therefore hypothesized by the authors that drivers' main problem in safe vehicle following derives from difficulty in evaluating risk and hazard, rather than from the limitations on the sensory and perceptual abilities which underlie most of the previous explanations driver behavior.

Regan, Hamstra, and Kaushal (1992) discussed two perceptual tasks that drivers use to navigate their vehicles safely: time-to-contact and heading estimation. This research suggests that the human visual system is particularly sensitive to time-to-contact when viewing objects in the central field of view. This sensitivity decreases as objects move into the periphery. Therefore, if drivers are attentive, their ability to judge time-to-contact is accurate. If drivers are attending to another object in their central field of view, and the lead vehicle is located in their peripheral field of view, then their ability to judge time-to-contact is greatly degraded. Thus a signal which could direct a driver's visual focus to the central field of view would be beneficial.

Mortimer (1990) also discussed these perceptual tasks. His research suggested that drivers are relatively sensitive to changes in headway or visual angle at large distances (he found a Weber ratio for headway detection change of 0.12). However, drivers are not sensitive to changes in relative velocity except at very short distances between vehicles. At inter-vehicle distances of approximately 400 feet or less, the rate of change of visual angle provides an added stimulus and even provides a crude measure of the magnitude of the rate of closure. However, the author maintains that the lack of information about the magnitude of relative velocity until the vehicles are in close proximity to one another is the primary cause of rear-end collisions.

Cavallo, Berthelon, and Mestre (1996) conducted a study in which they attempted to determine the role of environmental cues in drivers' time-to-collision judgments. Using a simulated collision task, they found that as the visual environment is enriched, drivers' judgments of time-to-collision becomes more accurate. Rich visual environments equalized these judgments over various approach speeds and actual times-to-collision; for impoverished visual environments,

approach speed and actual time-to-collision had a large influence on judgment of time-to-collision.

Hoffman and Mortimer (1996) conducted an experiment to determine whether subjects could use a ratio scaling method to estimate the relative velocity between two vehicles. Previous work by Hoffman and Mortimer (1994) had shown that the threshold value for perception of angular velocity is 0.003 rad/s. The main finding of this experiment was that only when the subtended angular velocity of the lead vehicle exceeded this threshold were subjects able to scale the relative velocity. Also interesting was the fact that some subjects (with little or no math or science background) performed much worse at this scaling task than did groups of engineering students. Hoffman and Mortimer attributed this to the engineering students' greater familiarity with the concept of ratios. The perception of relative velocity was non-linear, with a Stevens' power law exponent of approximately 0.8. The main implication of these findings for the present study is that traffic flow models that include human visual characteristics should consider the dead zones that occur when the thresholds for subtended angle change and subtended angular velocity are not met.

Recently, Gray and Regan (2000) reported on a phenomenon discovered in a simulator study of overtaking behavior. By varying the adaptation stimulus and the road texture, they found that drivers initiated overtaking substantially later following an adaptation condition of driving on a straight, empty road for five minutes (other adaptation stimuli included driving on a curvy road for five minutes, and five minutes of contraction adaptation caused by driving backwards). This effect was reduced by removing the road texture. The implication for driving is that after a prolonged period of high-speed driving while looking straight ahead at an empty road, a driver will overestimate the time-to-collision and be at risk of hitting the lead vehicle in the rear while attempting to pass. In some cases, the time headway was less than one second when the driver initiated the overtaking maneuver. However, this situation (long, straight, high-speed empty roads) is not the norm for most of the United States, and the situation described by Gray and Regan would thus have implications for only a small percentage of rear-end crash scenarios.

More research is required to understand the human visual system's sensitivity to speed, distance, and time-to-collision information. The driving environment is rich with visual information and it is currently impossible to isolate single sources of information to determine the relative importance of time-to-contact (or closure) versus relative velocity. It is important to remember that rear-end collisions are, relatively speaking, rare events. The human visual system is extremely sensitive to many sources of visual information, and drivers perform remarkably well in most circumstances. It is also possible that drivers are able to train themselves to become more sensitive to these cues as their driving experience increases.

#### Visual Factors in Warning Lights

While the photometric qualities of light, such as the intensity and size of lamp, have been discussed as these relate to the human visual system, other aspects (e.g., flash frequency, apparent motion, and the use of aural warnings) have not been addressed. Cohn (1993) conducted a study using simple integration models of the human visual system to describe human perception of flashing warning signals. Using strobe-type lamps, flashes separated by 30 to 80 ms decreased signal detectability by as much as 50%. Generally, the human visual system

cannot detect flashes that are separated by less than 80 ms, with the result that the second flash is not perceived as a flash, but rather as a non-flashing light. Strobe lamps must emit light flashes greater than 80 ms apart for the strobe to be effective in capturing a driver's attention.

Gros, Pope, and Cohn (1996) conducted a study investigating the apparent motion of spot stimuli. The results were that apparent motion stimuli are detected more efficiently than are non-moving stimuli. There are some rear-lighting systems, discussed in other sections of this report, that use apparent motion in the design of the brake lights to improve detection. They are therefore consistent with the Gros et al. findings.

### **Patents and Unpublished Literature Organized by Type of Information Presented**

Besides searching for new rear-signaling concepts in the open literature, several other sources were pursued. The following research results consist of rear-signaling concepts that were not found in the open literature but instead were presented to FHWA/NHTSA via letter/disclosure, found in patent searches, or found in internet searches (websites). The sheer number of ideas requires that they be classified in some logical fashion. Here, they have been categorized by the type of information presented, and in some cases, by type of system. Note that the ideas are at times repetitive and overlapping, but the volume of ideas is an indication of the number of people who see a need for improvement in the current rear-signaling system.

#### Information Presented: Brakes Have Been Applied

In these concepts, the following driver is presented with information indicating that the brakes have been applied in the lead vehicle. Some of the signal concepts indicate normal braking while other concepts indicate hard braking. The ideas are grouped by similarity in presentation and/or activation.

A number of rear-signaling concepts use color coding in some form to indicate that the brakes have been applied. In an unsolicited letter to NHTSA in 1989, a private citizen described the "vehicle signaling system." This system is a variation of the "red = brakes, amber = neither, and green = accelerator" concept. The three colors would be presented in a CHMSL-position housing with four compartments: the right and left sides would have red lights, the top center position would have a green light, and the bottom center would be occupied by a yellow or amber light. The information presented was very sketchy, and it appears that a patent was never issued for this device.

In an unsolicited letter to NHTSA in 1991, Cameron (1991) described a preliminary study of the Red Light Means Stop (RLMS) approach, in which red lights would only be used at the rear of the vehicle when the brakes are being used, and amber lights at all other times. This idea was patented by Cameron in 1987. This invention would allow only red lights when the brakes are applied, and only non-red lights the rest of the time. The rationale is that it would eliminate confusion caused by red running lights and turn signals. However, if the turn signals are activated during braking, they would be red, and would be another color when not braking, possibly creating confusion about the intention to turn (Cameron, 1987). A more sophisticated study of this device was subsequently conducted, and the article based on this second study is detailed in the open literature section of this report.

The patent issued to Arsoy (1979) describes an invention used to indicate hard braking. When the brake pedal is depressed to a certain degree, the red brake lights would illuminate, followed by the yellow turn signal lights (the inventor was from another country, which may have required yellow turn signals at the time of this patent; in the United States, yellow turn signals are still not required on vehicles, although they are becoming more and more common). When the brake pedal is released, the yellow lights would extinguish first, followed by the red brake lights.

Thurman (1986) developed a vehicle motion signaling system to be activated when the vehicle is in motion *and* the brakes are being activated or deactivated. The system is comprised of lights at both the front and rear of the vehicle that are purple in color to distinguish them from the usual brake lights. This system would act in conjunction with the current brake light system. This system was patented in 1986.

Over the years many inventors have proposed that the brake lights flash in some way to get the following driver's attention. The Signal Dynamics Corporation (1991) sent an unsolicited packet of information to NHTSA on the Brake Light Signal Module. The system is a device that causes the CHMSL to flash whenever the brakes are applied. The flashing pattern is different for this system than for some others that have been proposed: three short flashes followed by a longer pulse, with each cycle lasting ~6 seconds. The flashing pattern would continue as long as the brakes are applied. When the vehicle is backing, the light would flash continuously. This device was patented by its inventor, Jakabowski, in 1991. The device has been marketed to the public, and the most recent version of the device is available for sale at <http://www.signaldynamics.com>. The description of the device on the website uses the same pattern of flashing described in these documents.

The Brake Light Signal Modifier (private citizen, 1995) is another variation on the flashing brake lights theme. This system is described in an unsolicited report to NHTSA. The brake lights would flash rapidly (4 Hz) during hard braking, an abrupt stop, or whenever the brakes are applied twice in rapid succession. After a predetermined number of flashes, the brake lights would revert to normal operation. For deceleration without braking, the brake lights would flash at 1 Hz when the speed reaches 15 mph. Under all other circumstances, the brake lights would work as usual. This document contains four specific configurations of this device, detailing different methods of determining vehicle speed, different mounting options, and different connection options (one configuration is a stand-alone model, while others are tied into the vehicle's electrical system). Although the document states that a patent has been applied for, a search of the United States Patent and Trademark Office (USPTO) database showed that this device had not been issued a patent as of January 2001.

In a series of unsolicited letters and packets of information to NHTSA in 1999, an innovator requested forms for registering an aftermarket lighting system for sale in the United States. The device is an aftermarket 42-bulb LED CHMSL. The device can be set to one of three modes, which affect the braking, turn signal, and hazard lighting pattern. For braking, one of the modes causes five fast blinks of all of the red LEDs when the brakes are first applied, followed by a steady on state. This mode automatically shuts down in "stop-and-go" traffic. The other actions of the device are not of as much interest to this project, except to note that if every vehicle had one of these devices, and there were three modes of operation allowed, there would be a severe

lack of standardization of rear signals. The device appears to be available for sale in Japan at present, but has not yet been issued a U.S. patent.

Another innovator (2000) has a web site (<http://www.brake-alert.com/products>) devoted to the sale of a product called the Brake Alert, which causes the CHMSL to flash rapidly when hard braking occurs (deceleration  $>0.3g$ , or when a seat belt locks). At all other times the CHMSL works in the usual manner. The device is said to be even more effective when used with the newer LED strip-type CHMSLs. The device is described on the web site as patent pending (no patent was found for this device as of January 2001). More information on this device is presented at <http://www.brake-alert.com/info.htm>.

A patent issued to Purdy in 1978 describes an invention that would create a single bright flash of light from a strobe whenever the brakes are activated. The flash would be short in duration, lasting only micro-seconds. In addition, it would be tied into the turn signals and emergency flashers so that activation of these devices would also initiate a bright flash of light.

Sullivan (1983) invented and patented a system that would be inserted within a conventional brake light system. When the brakes are activated, the brake lights would flash on and off several times, then the brake lights would remain continuously lit. When the turn signals are on, however, the circuit would be disabled, and the brake lights would work in the normal manner, to avoid confusion caused by multiple flashing lights. Basically, this invention is another variation on the flashing brake lights idea.

In yet another variation of the flashing brake lights idea, a patent issued to Rosario (1987) describes an invention that would cause the brake lights to flash when the brakes are applied. The lights would flash rapidly two or three times, then would be on for a longer time, then would flash twice rapidly, then would be on again for a longer time.

A patent issued to Stanulis (1991) describes another variation of the “flashing brake lights for hard braking” idea. In this case, the signal is generated by a step increase in fluid pressure in the brake lines, which occurs only with very hard and sudden braking, according to the inventor.

Browne and Chin (1991) were issued a patent for a device that causes the brake lights to flash at a high rate (not specified) whenever the anti-lock brakes are activated. In one modification, there would also be a chime to alert the driver that the brake lights are flashing and that the anti-lock brakes are activated. Of course, ABS activation varies with vehicle make, model, body style, and other standard equipment, and ABS is not yet present on all models.

In an invention patented by Echt (1995), the brake lights would flash whenever the deceleration rate indicates “panic braking” (once the panic threshold is reached). The brake lights would remain flashing as long as the brakes are applied. This device is similar to several other inventions.

The patent issued to Egger and Egger (1997) describes an invention which causes the brake lights to flash under conditions of hard braking. Under light or normal braking, the brake lights



would work in the standard manner. This idea is similar to many others who advocate a flashing brake light to indicate hard braking, but uses different mechanical methods to achieve the result.

A device patented by Erlandson (2000) purports to better inform the following driver that the brakes have been applied. With this device, the instant the brakes are activated, a white light is flashed for 250 ms to attract the following driver's attention. The inventor describes this flash of light as a 'subliminal' flash-back alerting device and has named it STOPWHITES™.

Michelotti (2000) was issued a patent for a device that informs following drivers that the lead vehicle is performing a hard braking or sudden stopping maneuver. This device would activate the hazard lights as well as the brake lights under conditions of hard braking or sudden stopping. The hazard warning lights would be under separate control from the brakes so that if the brakes were not applied in a crash situation, the hazard lights would still be activated.

A device patented by Hemingway (1999) would activate a rear warning light whenever outside weather conditions are dangerous. Based on sensors for detecting deceleration, outside temperature, activation mode of the windshield wipers, and activation mode of fog lamps, the brake lights would flash when adverse weather conditions are detected. Otherwise, the brake lights would operate normally. The system could also function as an alarm system to prevent vehicle break-ins. This appears to be the only proposed system that takes adverse driving conditions into account and operates warning lights automatically under those conditions.

The concept of apparent motion (in which the lights appear to move through sequential activation) is related to flashing. Cohn (1996) was issued a patent for a brake light system that relies on apparent motion to make the braking of the leading vehicle seem more urgent to the following vehicle. There would be two brake lights on either side of the vehicle's rear end. The innermost lights would light up for 5 to 50 ms upon application of the brakes. After they have been on for 5 to 50 ms, the outermost lights would turn on for the duration of the braking event, and the innermost lights would turn off. The theory is that an observer would rapidly perceive the brake lights as looming closer, due to the inward-to-outward sweeping visual image that enhances salience. Because the observer's M cells appear to be primarily stimulated by the luminous energy, the observer can react more rapidly to the braking action than with conventional brake lights. (M cells are magnocellular cells, or large retinal ganglion cells, which respond well to visual stimuli that are rapidly turned on and off, and to moving stimuli.) The use of apparent motion appears to stimulate rapid M cell response in an observer's visual system. This is one of the few patents containing scientific detail on the reason the proposed system would decrease reaction time. Most patents ignore this issue, or simply state that the desired effect will occur, without providing evidence for the claims.

Note that the patent by Cohn (1996) does not address the issue of reactivation. If there is no time interval between the outer to inner activations, then the rear lighting would appear to increase and then decrease in separation, rather than showing an increase followed by another increase. On the other hand, adding a delay might decrease detection or increase reaction time.

Still other concepts use a combination of modes for presenting the information, such as color coding combined with motion or flashing combined with a warning word. The patent by Lange

(1998) describes an invention that would have two sets of light-emitting diodes running around the top and sides of the rear window of passenger vehicles. The first set would be red, and when the brakes are applied, the diodes would light up in sequence, beginning at the center top of the window and running down both sides (then presumably beginning again). The second row of lights would be yellow arrow-shaped diodes that would work in much the same way when the turn signal is used, except that only the side for the intended turn would light up.

The patent issued to Mucciacciaro (1998) describes an invention consisting of a rectangular plate mounted on the back of the vehicle, with the words “slow down” (or some similar warning) stenciled in the plastic covering. When the vehicle brakes, the sign would light in a steady manner. If the brakes are activated for two seconds or so, a strobe light would flash behind the sign. After four seconds or so, the strobe light would deactivate. If the brakes are released at any time, both the steady burning lamp and the strobe light would be deactivated.

Other inventors would keep the current system of brake lights intact, while making modifications to the activation system or hardware. Chicoine was issued a patent in 1978 for an invention that would cause the brake lights to activate whenever the manual transmission is downshifted. This is similar to other ideas for early warning brake lights and deceleration warning systems. As manual transmissions have become less prevalent, this invention has become less relevant. This device was intended to be manually operated, and could incorporate a flasher unit to cause the brake lights to flash during activation.

Hart (1986) was issued a patent for an invention that would house a brake light within the side-mounted rear view mirrors. The idea is that as the brake lights are extended away from the body of the car, they would be easier to see from the rear (this would effectively make the car look wider/closer than it really is). A similar idea has been implemented recently on some light trucks in which a red chevron shape in the outside mirror is illuminated with the directional signal.

A patent was issued for a device (described earlier) that preheats the filament of the brake lamp and supplies an over-voltage when the lamp is activated, resulting in faster lighting of the brake lamp. The inventors predicted a 115 msec reduction in reaction time with the device installed, based on simulated tasks (Flannagan and Sivak, 1988). At 60 mph, this could result in an extra 10.1 feet of stopping distance.

Alhassoon (1999) was issued a patent for an invention that would delay the brake light deactivation beyond the time when the brake pedal is released. This would be done by means of a delay timer inserted into the fuse box in the position currently occupied by the brake light fuse. Another feature of this device is that the delay (in seconds) could be adjusted by the user (note that user adjustability features further erode the standardization of rear-lighting systems).

The patent issued to Slater (1999) describes a system in which the brake lights would be activated whenever the horn is used, even if the brakes are not applied. There would also be a steering wheel-mounted switch for the driver to manually activate a CHMSL flasher. A dash-mounted indicator light would show the status of the brake lights to the driver, so that when using anti-lock brakes, the driver would be reminded not to pump them during hard braking (by seeing the flashing of brake lights on the dash-mounted indicator light). This approach seems

rather specialized compared to many of the systems being proposed, especially as drivers become more used to driving with anti-lock brakes, and as horns are used less frequently to warn of road hazards.

#### Information Presented: Deceleration

The concepts described in this section present the following driver with information about whether the lead vehicle is decelerating, without regard to whether the brakes have been applied. Note that deceleration is a continuum, and thus many ideas require a graduated display to present the information. Others, however, use a criterion of deceleration, and thus a two- or three-stage signal is used. Again, ideas are grouped by similarity in mode of presentation or activation.

Some deceleration concepts simply require that the deceleration exceed some set point before a signal is presented. In 1994 a private citizen described a brake warning indicator in an unsolicited letter containing a patent application. This system would warn of vehicle deceleration. It would be activated by decreases in both vehicle velocity *and* engine speed. The standard brake lights would be activated when both conditions are met regardless of brake activation. From a search of the USPTO database, it appears as though a design patent was issued for this device, but the design patent consists wholly of drawings, with no descriptive text. The device as technically described in the application has not yet been granted a patent.

In an unsolicited proposal to NHTSA in 1996, an innovator described a rear-lighting system, similar to many others that have been proposed, which would provide an indication of braking urgency to the following drivers. This one differed in that the signal would be based on inline brake fluid pressure (rather than accelerometer output) and in that three colors of red would be used (dark or dull red for light braking, medium red for medium braking, and “hot” red for hard braking). There would be three pairs of lights arranged horizontally, and they would be lit from the outside inward as braking urgency increased. The CHMSL would be lit with the outer lights to indicate light braking.

Another private citizen submitted an unsolicited letter (with patent applications enclosed) to NHTSA in 1996. The patent application describes an invention that would use green and yellow lights to warn of acceleration and deceleration. Green lights would be used to indicate acceleration and yellow lights to indicate deceleration. When the vehicle is moving at a constant speed, no lights would be used (in many systems, green lights are proposed for running lights). No mention is made of red lights, so the assumption would be that they are activated as usual by use of the brakes. This device does not appear to have been issued a patent as of January 2001. Much of the discussion centers around the logic for activating the lights to avoid false alarms and annoyance, and in the method for detecting acceleration and deceleration of the vehicle.

In a letter to NHTSA in 1997, a private citizen provided answers to questions posed in Docket No. 96-41, Notice 1, of NHTSA. The bulk of the document consists of a description of the concept, which is another color-coded system using green, yellow, and red. The arrangement of the lights is somewhat different from other color-coded concepts, with nine lights contained in a single housing unit mounted in the rear window of the vehicle (in or near the CHMSL position). The combination and action of the lights is fairly complex, and depends on vehicle speed

(several pages are used to explain the various lighting combinations). No patent appears to have been issued for this device.

In an internal report for BMW, Fenk (1998) provides details of research being conducted using BMW's driving simulator to provide a differential display of braking strength to reduce the number of rear-end collisions. A design matrix was developed to determine the most effective parameters. This is similar in function to the trade-off analysis performed for the current study. The matrix is reproduced in Table 14 below:

**Table 14. Parameter/criteria trade-off matrix for rear lighting.**

Parameter Criteria	Color	Light intensity	Lamp Geometry			Frequency	Number of stages	Raised brake light
			Position	Area	Shape/ contour			
Behavior at distance	?	4	3	5	0	2	3	3
Interpretability	0	5	5	5	3	0	5	3
Urgency character	?	4	3	5	2	4	2	4
Perception level	0	3	3	4	0	5	3	5
Acceptance	?	3	4	5	1	1	5	3
Natural zero point	0	2	5	5	0	0	5	4
Minimization of burden on driver	0	2	5	5	1	1	5	3
<b>Score</b>	<b>0</b>	<b>23</b>	<b>28</b>	<b>34</b>	<b>7</b>	<b>13</b>	<b>28</b>	<b>25</b>

There is no supporting rationale for the scoring of the individual parameters, which makes it seem as though they were assigned subjectively by one person. Those parameters determined to be candidates for encoding braking intensity were studied further in a series of experiments (mostly simulator). The experiments are not well described (for example, the number of subjects is not provided in the report). The report concludes by recommending a three-stage braking intensity system. In light braking, the two lower brake lights would activate. With moderate braking, the two lower lights plus a CHMSL would activate, and the lower lights would burn at a higher intensity than for light braking. With strong braking, the two standard brake lights would become larger and the CHMSL would become wider (an LED-type CHMSL strip was used). Field tests of this multi-stage braking intensity system were described.

In another internal report for BMW, Fenk (1999) details further work on the brake force display apparently developed by BMW. A three stage system was designed in which: 1) light braking causes the standard (two lower) brake lights to activate at a medium intensity, 2) medium braking causes the CHMSL to activate and the two lower lights to increase in surface area and intensity, and 3) heavy braking causes the CHMSL width to be increased and the surface area of the two lower lights to be further increased.

Tests were run on a test track and on an autobahn. For light braking on the highway, reaction times were slightly longer with the brake force display as compared to standard brake lights.

The author attributes this finding to the additional information provided by the display; in light braking situations, the following drivers could drive safely while waiting longer to apply their own brakes, because they knew that this was not an emergency braking situation. (Note: this may also be a sign of risk compensation, which is a potential problem with almost all new rear-lighting designs.) For medium braking on the highway, there was a slight reduction in reaction time with the brake force display as compared to standard brake lights. For emergency braking, tests were only conducted on the closed circuit track for reasons of safety. For both light and medium braking, there were no differences for the test track scenario, and this also proved to be the case with emergency braking. The author attributes this to the fact that drivers on the closed circuit course were able to devote all of their attention to staying alert for the brake light signal, resulting in almost equal reaction times across the two lighting configurations, as well as reaction times that were significantly shorter than those found under highway conditions. The author thus extrapolates that the brake force display would result in reduced reaction times on the highway, based on the medium braking results. This is one of the few studies in which a proposed rear-lighting design has undergone rigorous testing, both in a simulator and on the road.

Fenk (2000) later obtained a patent for a process and arrangement of brake lights to display braking intensity information to following drivers. This design utilizes and enhances a natural property of our visual system. As we approach another vehicle, it occupies more space on our retina and the lights appear brighter. In this design, the brake lights imitate and enhance this visual property by increasing in size and brightness as braking intensity increases. The braking intensity is presented in three discrete steps: low, medium, and high deceleration.

Poulos (1989) was granted a patent for a brake light flasher device combined with a deceleration indicator. In this invention, the brake lights would flash while the vehicle is undergoing a certain degree of deceleration. After a specified time, the lights would stop flashing and burn steadily.

Vinciguerra and Durivage (1994) were issued a patent for a motor vehicle anticipated warning device. This is another variation of using an amber light to indicate deceleration. This design differs from some of the others in that there is a time delay included so that for any one of a number of pre-defined events, such as a momentary deceleration followed by re-acceleration, the amber light would not illuminate. Also, if any of the pre-defined events occur while the amber light is activated, it would be extinguished. The brake light would apparently continue to function as normal (the red brake lights would be activated only when the brake is depressed).

Mason, Olliver, and Watkins, (1999) were issued a patent for a device that is unusual in that the deceleration detector is plugged into the lamp socket (the lamp then plugs into it). Once a certain rate of deceleration is detected, a strobe light would flash (a strobe is the preferred warning, although LEDs, incandescent bulbs, or the normal brake lights could also be made to flash). The uniqueness of this device is in the relative simplicity of the deceleration detection. The suggested use of a strobe warning light is also unusual.

Other inventors have proposed a variety of methods to convey deceleration *rate* information to the following driver. Since the rate is a continuous variable, a display capable of providing continuous information is often required. The most common display concept for this situation is to use a horizontal light bar which lights up sequentially starting at either the inner or outer set of

lights. Other concepts use intensity coding, flash coding, and auditory warnings to provide this continuum of information.

One of the most elaborate designs comes from Barske and Gerhaher, who proposed an “intelligent” stop lamp in 1996 (in an unsolicited report to NHTSA, followed by several letters and a videotape). The “intelligence” is based on the calculation of a danger rate,  $G$ , based on several braking factors (deceleration, braking period, and initial speed). They propose that the danger rate could be made evident by using light intensity, light size, or frequency (flashing) of the stop lamp. A related article is discussed above in the publications section. A patent was later issued to Gerhaher (1997) for this device. A demonstration videotape of this device was viewed in preparing this literature review. It shows that the most recent version is a device that provides information about the danger rate,  $G$ , by using changes in light intensity as well as blinking. A light bar lights up from the outside-in depending on the value of  $G$ , and times out after a certain amount of time (which also depends on the value of  $G$ ). It should be noted that the test equipment for this research was mounted in the instrument panel of the following vehicle, not the rear of the lead vehicle.

In a proceedings article, Parpia (1993) suggested a system that might aid the driver in improving braking response under conditions of fatigue and/or poor visibility. The device consists of an inside-out horizontal array of lights on the rear of the vehicle, with lights activating in pairs from the center towards the edges in relation to the degree of deceleration of the vehicle. In addition, the driver of the following vehicle would have a miniaturized version of the display on the dash or windshield. This would allow the following driver to compare his or her own rate of deceleration with that of the leading vehicle, to see whether braking is sufficient, and to not have to take the eyes off of the forward view. In the paper, this in-vehicle display idea is credited to Wierwille (1993).

A patent was issued to Salsman (1992) for a system in which an inertia-activated switch would sequentially activate pairs of lamps from the inside out (the center pair first, followed by the next to center pair, etc.) to create a wide horizontal bar of light for hard braking and a narrower bar for lighter braking. The innovation in this design is in the inertial switch, and some of the design elements to ensure that the inertial switch works properly under all driving conditions. The inventor enclosed a description of his invention in an unsolicited letter to NHTSA (1994). This is not a new idea, although the inventor seemed to think that it was. Some of the switching and sensing mechanisms are new to the particular system, however. Another unsolicited letter to NHTSA in 1994 further explained some of the advantages of this invention.

A private citizen, in an unsolicited proposal to NHTSA (circa 1996), suggested the Comprehensive Deceleration Advisory System. Four categories of braking/deceleration were defined, with different light activations for each. For ordinary deceleration, rear amber lights would be activated; for ordinary braking, the usual red brake lights would be activated while the amber lights would remain lit; for serious braking, the red brake lights would intensify in illumination or blink momentarily (once every two seconds); and for panic braking, the red brake lights would intensify in illumination or blink rapidly (four times per second) and continuously. The red brake lights would be above the amber deceleration lights in keeping with the coding used for traffic signals. In a reply, a NHTSA representative states that this proposal is similar to

work on deceleration lights that NHTSA sponsored years ago, which did not yield significant results.

A patent was issued to Lurie, Putnam, and Tabib (1996) for a braking system having variable intensity light and sound warning. This is a system in which the brake light intensity would increase with increasing deceleration, similar to several other systems that have been proposed. This system differs in that, under conditions of hard braking, both a strobe/flasher and an audible signal would be presented to the following driver. This is one of very few proposals advocating an external auditory component, and the potential for annoyance resulting from noise pollution is not addressed in the patent.

The patent issued to Gilmore (1997) describes an invention that would allow the brake light intensity to be governed by the amount of vehicle deceleration (the higher the deceleration rate, the greater the brake light intensity). A further feature is that if the deceleration exceeds a certain limit, the brake lights would also begin flashing.

Li (1997) was issued a patent for an invention in which acceleration would cause a sequential activation of green lights depending on degree of acceleration, and deceleration would cause a similar sequential activation of red lights. Both light bars would operate on the inside-out principle (that is, the light bar would grow wider from the interior set of bulbs as acceleration or deceleration increases). The invention appears to differ from other similar ideas in two ways: 1) the mechanism for detecting acceleration/deceleration, and 2) in the fact that it is a stand-alone aftermarket add-on device.

The patent issued to Schroeder (1998) for an electronic device to indicate the acceleration and deceleration for vehicles contains technical detail on detecting the acceleration and deceleration of the vehicle. However, it contains very little information about the type of display to be used, except that it is the form of “at least one luminous display” composed of a “plurality of luminous elements.” The elements would be successively activated and deactivated with the changing position of the accelerator. There also appears to be a flashing component to the system, although its purpose is not clear from the description provided. The light color and mode of activation (inside-out, outside-in, left-to-right, etc.) are not mentioned.

A design patent for a variable intensity brake light was issued to Allen (2000). No details of activation are presented in this patent. From the drawings, it appears that the device consists of a long row of LED lights, arranged in a strip and mounted in the CHMSL position.

Robert (2000) was issued a patent for an invention that would use either light intensity or flashing related to the rate of deceleration (note that this is one of the few, if not only, systems to propose a flash-coded deceleration indicator). Another sensor would recognize tire slippage or stoppage due to a slick road surface or traffic crash, and activate a high intensity visual warning signal when this occurs. The system would be controlled by a microprocessor, and could be programmed to perform other functions or variations of the described functions.

Demko (2000) was granted a patent for a device that presents rate of deceleration information. This device consists of a horizontal line of eight lights. The lights vary in size and intensity with the two innermost lights being the smallest in diameter and lowest in intensity and the two

outermost lights being the largest in diameter and brightest in intensity. As deceleration increases, pairs of lights illuminate in succession from the center of the horizontal line of lights in an outward direction.

#### Information Presented: Stopped Vehicle

This section focuses on concepts that present the following driver with information that the lead vehicle is stopped. In some cases, there are also other modes of operation for the rear-signaling system, but these are the very few proposed systems that provide *any* stopped vehicle information.

Tonkin (1997) described the Pamela Anti-Crash System (PACS) in a technical report. This system has several modes. For stopping, this device has a horizontally arranged set of lights that extinguish in sequence from the inside out with repeating cycles. All the lights activate initially, then they begin turning off in pairs, very rapidly, to create an illusion of motion. There is also a proximity sensor, and when a vehicle is detected close behind the PACS vehicle, the light switches to a steady burning three-light stopped configuration. Another mode is a progressive brake warning (deceleration) mode, in which the light pairs activate sequentially as deceleration increases, from the inside out, as has been suggested by several innovators. This system differs from many others in that there is a specific mode for demonstrating that the vehicle is stopped, as opposed to decelerating or braking. Tonkin, Hall, Strong, and Cucinotta were issued a patent for this device in 1999. The device described in the patent is essentially the same as described in the report.

In an unpublished research report, Ward and Parkes (1998) discussed an evaluation of a proposed collision avoidance brake light system. The concept is a brake light system comprised of an oversized high-intensity LED array attached to the CHMSL. The extent of array illumination would correspond to the extent of deceleration of the vehicle (via an inside-out expansion of light pairs corresponding to increased deceleration) and would include an animated display to alert traffic when the vehicle is stationary (at a flash rate of 2 Hz). The device is called the Collision Avoidance Brake Light System (CABLS) and is purported to provide both improved conspicuity (being large and bright) and information (on deceleration rate). The design was evaluated via a simulator, using 55 subjects, and included a condition in which the CABLS flashed randomly (same intensity but no deceleration information). The simulator results did not show a statistically significant improvement in safety with the CABLS system, but the results were promising enough that further research was planned. In a seminar presentation on the CABLS device, Ward, Parkes, Arron, and Jamson (1999) indicated that the data collected in the simulator study was subjective preference and understanding data, not reaction time data.

Cooper, Dingus, and Lee (1999) performed an assessment of an innovative rear-lighting signal for collision avoidance. It involved installing a rear-facing sensor and a high visibility white strobe warning light which would flash when the car was in danger of being hit from behind. As later tested on a closed test bed highway, the device was used to alert subjects to an unexpected stopped vehicle. This device showed mixed results (depending mostly on the age of the driver), but it should be noted that the sample size was rather small.



The device described in the patent issued to Ingram (1982) would cause the brake lights to flash when the brakes have been activated for a certain amount of time or when the vehicle is stopped and the brakes are on. The lights would quit flashing when the brakes are released. Note that in this system, the brake lights would flash either when the vehicle is close to stopping or is stopped, and the brakes are being used. This is one of the few systems that addresses the problem of notifying following vehicles of a stopped vehicle ahead.

#### Information Presented: Safe Following Distance

Other inventors have come up with concepts that provide information about the safe following distance to the following driver. Caine (1986) was issued a patent for a light box that would be situated in the rear of the vehicle at the eye height of following drivers. The box would be illuminated, but there would be opaque areas through which the light could not pass. The opaque areas would be of increasing thickness. As a following vehicle approaches the lead vehicle equipped with the light box, the lights would progressively appear, giving the following driver clues as to the safe following distance. Likewise, when the distance is greater, the light would appear to be a continuous bar, letting the driver know that the following distance is safe. In other words, the concept of spatial frequency would be used; the lights would appear to fuse at greater distances, and would begin to appear as separate lights as the following vehicle neared the lead vehicle. Ideas for colored lights, such as green for acceleration, are presented in the patent, as well as ideas for allowing the system to flash for emergency stopping.

Caine (1976) was issued a patent listing three possible embodiments of a system that would signal the following driver when he or she is too close to the lead vehicle. These systems are based on characteristics of the visual system, such as fusion, in which individual illuminated windows assigned to different safe speeds would merge together when the following distance is adequate, but would be seen separately when the following distance is too short. Another version works on the same principle, but with dark areas rather than illuminated areas, while a third version uses color discriminability in a similar fashion.

In a letter to NHTSA, Bleiner (1995) described the Astron One Safety Driving System. This device is different from others examined in that it proposes the use of a laser beam to indicate safe following distance. The high visibility of the laser, as well as its ability to penetrate fog and rain, are listed as advantages of this type of display. The laser would shine down on the road, and as long as the following driver can see where the laser meets the road, then the following distance is safe. When the following driver gets too close, the laser appears to crawl up the hood of the following car, thus alerting the driver to the potential of a collision. Different colored lights are proposed to indicate braking versus acceleration or presence, as well as pulsing of the laser as a stopped vehicle signal. Specially designed lasers are proposed for special vehicles such as trucks and buses, to aid in vehicle identification. A patent for this invention was issued in 1999. Of course, safety issues in using lasers must be addressed before this type of device could be approved for use on vehicles.

#### Information Presented: Release of Accelerator

Still other inventors have proposed that providing the following driver with a warning of when the lead vehicle driver releases the accelerator would decrease rear-end crashes. In an unsolicited letter to DOT and NHTSA in 1995, an innovator informally proposed a system that

signals deceleration by using the existing white rear back-up lights. Solid white lights would be activated when accelerator pressure is decreased by a certain amount and extinguished either by additional accelerator pressure or by the activation of flashing white lights when the accelerator is totally released. The flashing white lights would remain activated until either the brake or the accelerator is depressed. The flashing white lights would also be activated whenever the vehicle is stationary and in forward gear, and a solid white light would be used when the vehicle is shifted into reverse. This was a concept-only proposal; there was no product built to perform these functions. This is one of only a few ideas which included an increased use of white light for rear signaling.

Blount (1995) was issued a patent for a system in which an amber light would be activated when the foot is released from the accelerator to warn the following driver that the lead vehicle is slowing. The brake light would apparently continue to function normally (the red brake lights would be activated only when the brake is depressed).

The device patented by Marks (1999) is a variant of the proposed design of activating the brake lights whenever the accelerator is released. In this case, an optical beam would detect movement of the foot as it travels towards the brake, and the brake lights would then be activated. This system would not activate the brake lights in the case where the accelerator is released but the driver's foot does not move towards the brake (thus avoiding a false alarm problem often noted with other proposed systems). On the other hand, it seems that there could be a high proportion of false alarms due to normal leg and foot movement while driving. In a refinement to the patent, Marks (1999) proposed improvements to the circuitry for detecting the driver's foot motion, but the principle of early brake activation remained the same.

Woerner and Caine (1990) were issued a patent for a device that would use two switches attached to the accelerator pedal. The running lights would be induced to blink whenever the timing of the activation of the two switches meets a certain threshold indicating a quick release of the accelerator pedal.

A fleet study was performed to test an advance brake warning system (ABWS; Shinar, 2000) marketed by BARAN Advanced Technologies. This was a follow-on evaluation to a false alarm rate study (Shinar, 1995) and a Monte Carlo simulation study (Shinar, Rotenberg, and Cohen, 1997) of the same system. These earlier studies showed some degree of promise for this system in which the brake lights are activated by a rapid accelerator pedal release, providing an average of 0.25 seconds additional warning of brake application. However, the fleet study demonstrated ambiguous results at best. A total of 764 vehicles were studied for an average of almost three years each. Half of the vehicles were equipped with the ABWS, and these were each matched with an ordinary vehicle (all vehicles belonged to the Israeli government).

The results failed to demonstrate a benefit in terms of a reduction in rear-end collisions for vehicles equipped with the ABWS. There are three reasons why this system did not live up to its promise: 1) it was assumed to be most effective for an attentive driver following at a very close headway, and this situation may be relatively rare (Shinar, 2000, acknowledges that many rear-end crashes are caused by inattentive following drivers); 2) rapid accelerator releases are relatively rare events; 3) and the system had potential to be helpful for collisions in which the

lead vehicle stops or slows suddenly, but not in which the lead vehicle is stopped for some time before the collision. In summary, the ABWS had potential to be helpful for only a very small subset of rear-end crashes, and thus is not an avenue worthy of further pursuit for the purposes of this report. An interesting side note is that the author observed the difficulty in obtaining statistics for “relevant” crashes (those in which the lead vehicle stopped or slowed suddenly). In the course of performing the current report, the contract sponsor expressed interest in obtaining statistics about how long a lead vehicle had been stopped before the rear-end crash occurred. Based on Shinar (2000), accurate data of this sort would be difficult to obtain.

#### Information Presented: Blind Spot Identification

In an unsolicited disclosure of invention to NHTSA in 1996, a private citizen described the automobile blind spot illumination device. This invention is a device that uses directional lighting to inform following vehicles when they enter a lead vehicle’s blind spot. When the following vehicle enters the blind spot, a graphical message (Blind Spot) can be viewed, and it can only be viewed from the blind spot angle. The relevance to this project is that the device is located in or near the CHMSL position for passenger cars. The device can be combined with a CHMSL, according to the inventor. A search of the U.S. patent database revealed that this device has not been patented as of January 2001.

#### System Type: Closed-loop Systems

For some concepts, the type of system is more important than the type of information presented. This is true for closed-loop systems, in which information is passed from one vehicle to another. Beymer and Hochnadel (1994) proposed that a line of traffic resembles a chain in which information is sent forward and backward. A center high mounted warning lamp is proposed; this would provide information about the braking patterns of vehicles further up the chain that the driver might not be able to see. The system would require all vehicles to be outfitted with a device to both send and receive signals. There would be a dashboard display indicating chaining status, and the center high mounted warning lamp mounted on the rear of the vehicle would be yellow. One major disadvantage of this system is that nearly all vehicles would have to be equipped with the system before it would be effective (since all vehicles in a chain must be equipped with the system; even one car in the chain without the system would break the chain). The purpose of the system is to reduce reaction time by up to one second. A patent was later issued for this concept, and is discussed below.

The patent issued to Beymer (1995) describes a method for transmitting and receiving an electromagnetic data signal in a moving, linear chain. Motor vehicles are the units in the chain, and each unit has a processing unit interconnecting a directional receiving element, a directional low power transmitting element, a deceleration detector for the unit, and a deceleration detector for preceding units in the chain. If deceleration of a preceding vehicle, the vehicle itself, or an identifiable signal from a preceding vehicle (such as a blue light) is detected, a rearward facing blue light would illuminate. This blue light indicates to following motorists that the perceived vehicle is decelerating or that a vehicle somewhere in front of it is decelerating. The blue light may also be received by another vehicle equipped with the invention and consequently be transmitted to the rear. A data encoded signal is transmitted from the rear of a vehicle. This signal contains information relating to deceleration of any preceding vehicles (Chain Brake) and of the transmitting vehicle (Brake). A receiving vehicle analyzes and displays the data to

provide a motorist with information regarding preceding vehicles that may or may not be seen by the motorist. A variety of data is transmitted and received bi-directionally throughout the chain.

A patent was issued to Kutlucinar (2000) for a vehicular hazard warning system. This appears to be a closed-loop system. If an emergency situation is detected in the lead vehicle (air bag release, ABS brake activation, roll-over sensor activation, etc.), then a system in the following vehicle would inform the driver of the emergency situation, thereby providing the following driver advance warning of potential danger. It does not appear that the inventor has determined the best way to present this information to the following driver(s).

#### System Type: Programmable Turn Signal

In an unsolicited letter to NHTSA, Wadlington (1995) included a paper-presentation proposal describing AccuBlink, a device that emits a pre-established number of signal blinks each time a vehicle's signal lever is tapped. This is basically a programmable turn signal. The idea is of more relevance to turning and lane change crashes than to rear-end crashes. A further letter in 1995 described a proposed method to measure the potential safety benefits of the AccuBlink system. The device was issued a patent in 1996. It is unclear whether this device has been installed in any vehicles. Note that many of the concepts for rear-signaling systems propose blinking or flashing lights, and the possible interaction with the current turn signal system has rarely been considered. Demmler (1997) reported a short news article on the *AccuBlink* system.

#### System Type: Running Lights

The patent issued to Caine (1989) describes two lamps, one of which seems to be exactly like a CHMSL, and the other of which is a yellow light near the CHMSL which is illuminated whenever the brake lights are not activated. This yellow light would supposedly alert the following driver to the presence of the lead vehicle, as well as draw visual attention to the area of the CHMSL so that it would be detected more rapidly when the brakes are applied.

Cameron (1987) was issued a patent for an invention (previously described) in which only red lights would be illuminated when the brakes are applied, and only non-red lights would be illuminated the rest of the time. The rationale is that it would eliminate confusion caused by the use of red running lights and turn signals. However, if the turn signals are activated during braking, they would be red, and would be another color when not braking, possibly creating confusion about the intention to turn. Note that separation of color and function for brake lights have been recommended by Mortimer and others since the later 1960s.

#### System Type: Stop Lamp Improvements

An invention for which Chinniah, Wasilewski, and Patel (1997) were issued a patent would use a different lens and bulb design to achieve uniform lighting over the lens face, while the lighting assembly would also be reduced in depth. Although it sounds as though this might result in increased brightness at greater viewing distances than current designs, it is probably the sort of device auto manufacturers are free to install at present. It does not really propose any new information for the following driver, but merely describes one way that the light may be made brighter without sacrificing space.

Eberspacher, Gauch, Haf, and Robel (2000) were issued a patent for a variable intensity lighting system. The light intensity would be adjusted according to ambient light conditions to avoid blinding the following driver with glare at night and to provide increased intensity during the day and in fog. The operation of the system would be largely manual through a multi-position switch, although when the rear-facing fog lights are illuminated, they would be automatically dimmed on sensing a vehicle approaching from behind.

A patent was granted to Green (1976) for the invention of a double filament bulb, in which the second filament would be activated under foggy conditions. This would produce a higher intensity of rear light illumination under these reduced visibility conditions. Rear fog lights are common in Europe, but appear not to be used in the United States to date.

#### System Type: Truck Lights

In an unsolicited letter to NHTSA, Hymer (1996) described a product called Safety Hi-Lites, which are intended to be mounted high on the back of truck trailers. This is a retrofit device meant to prevent cars from running under the backs of trailers. The lights would be mounted facing the rear of the vehicle, at the top corners. The system includes a deceleration sensor and can be installed as an after-market device. The device was patented in 1998, and can be purchased online at <http://www.hi-lite-safetysystems.com/>.

A highly graphical document from the S.A.F.E. Foundation (1996) describes the Truck and Trailer Safety Signalight System, which is intended to be used on trailers. There would be two triangles of lights (similar to the CHMSL concept), one of which would be yellow to indicate running and the other would be red to indicate braking. There would also be lights along the side of the trailer to indicate running and braking. There is no research detail to support the claim that this device would shorten stopping time by 0.5 seconds.

In an unsolicited letter and packet of information to DOT in 1995, an innovator provided literature regarding the RPS “Blitz” engine brake activated stop light. This device is meant for trucks and other large vehicles that use engine brakes. Although the technical details are sketchy, the device would cause the brake light to be illuminated whenever the engine brake is in use. The device does not appear to have been patented.

In a report to the Governor and General Assembly of Virginia, Johnson and Stoke (1994) answered a Joint Resolution which requested that several state agencies (the Virginia Department of Motor Vehicles, Center for Innovative Technology, Motor Carrier Division of the State Corporation Commission, and the Department of State Police) conduct a study of the types of deceleration lights currently available, the desirability of allowing deceleration lights on trucks in the Commonwealth, and the appropriate standards that should dictate their use. The conclusion was that accelerator position lights should not be allowed on trucks in Virginia, but that a permit system should be established so that experimental testing of these types of devices could be allowed.

#### **Overview of Human Factors Research on Attracting an Operator’s Attention**

There is an extensive and time-tested body of basic human factors research on how visual signals can be coded to make them more salient to the observer, or to capture the observer’s attention.

These are often presented in the form of design guidelines for visual display design. Guidelines relevant for rear-signaling display design have been abstracted from the following sources: Sanders and McCormick (1993); Boff and Lincoln (1988); Wickens, Gordon, and Lui (1998); and Salvendy (1997).

### Visual Display Criteria

In designing a visual display, the criteria for success must be kept in mind. If a display cannot accomplish the following for the great majority of observers, then it should be redesigned. Any new rear-signaling concept should be evaluated on how well it meets these criteria. A visual display must do the following:

- Capture or direct attention to itself.
- Be readable (legible).
- Be understandable.
- Properly represent the concept or information.

### Forms of Information to be Communicated

It is also important to determine which types of general information are to be communicated. Rear-signaling concepts have been suggested that are capable of providing any of these types of information. For example, some proposed systems would have the brake lights remain on for a period of time after the brakes have been released, thus providing the following driver with history information about the past state of the system.

- Instructional - how to do something.
- Command - direct order of required action.
- Advisory - recommendation of action or notice to prepare for action.
- Status - current state of system.
- History - past state of system.
- Predictive - present plus expected future state of system.

### Modes of Coding Information

A decision must be made regarding how the required information is best presented to the observer (the following driver). Coding of information refers to the assignment of meaning to the various levels of the display methodology. For example, in color coding, the various colors take on different meanings (in a common example, red = stop, amber = caution, green = go). This allows a greater amount of information to be conveyed within a limited space. There are

many methods of coding visual information, and those most relevant for rear signaling are presented below.

- Color Coding, in which the color of the signal conveys information about the presence or degree of hazard. Due to problems with color blindness in parts of the population, this is rarely used without some other redundant coding scheme.
- Position Coding, in which the position of the signal conveys specific information about the hazard or the degree of hazard. This is often used in combination with other design concepts and coding mechanisms.
- Size Coding, in which the size of the signal changes in response to the degree of hazard present, or in which the mere size of the signal conveys information about the presence of a hazard.
- Flash Coding or Flash Rate Coding, in which 1) either the mere presence of a flashing signal, or 2) the rate at which the signal flashes, conveys information about the presence or degree of hazard.
- Apparent Motion, similar to both size and flash rate coding, in which, for example, the rate of change of size of the lead vehicle is exaggerated by using an inner to outer sequencing of lights.
- Intensity Coding, in which the intensity of the signal (auditory or visual) conveys information about the degree of hazard.
- Alphanumeric coding, in which numbers and letters are used to convey information (either in word form such as STOP, or truly coded such as BT54).
- Pictorial coding, in which a pictorial image or symbol is used to convey information. A common example of this is the wheelchair symbol used to convey information about handicapped accessibility.
- Shape coding, in which the simple shape of the display has an associated meaning. (For example, the octagon is commonly used to convey “stop” information, due to its association with stop signs, while the triangle is often used to indicate caution.)

#### General Perceptual Principles of Display Design

Finally, after having come to some decisions about what type of information to present and how best to present it, there are some general guidelines that will help the designer create an optimal visual display design.

- Redundancy gain: if the message is presented in alternative physical forms, it is more likely to be interpreted correctly.

- Similarity causes confusion.
- Avoid absolute judgment limits: on a single sensory variable like color or size, use no more than 5-7 levels.
- Top-down processing: people will use prior knowledge and expectancy, so if the display is contrary to this, make it more obvious.

### Color Coding of Lights

The current rear-signaling system makes some use of color coding, with red indicating that the brakes have been applied, amber or red flashing indicating an intention to turn, and white indicating that the car is in reverse gear and may be backing. In addition, a less intense red is used at night to indicate vehicle presence (running lights). Some designers have advocated adding green to these three colors, and one has even advocated purple. The following guidelines can be used to help decide how many and which colors should be used (it is assumed that the colors will be in the form of a light).

- *Design for monochrome first, then use color as a redundant backup.* Since approximately 7% of the male population suffers from various forms of color blindness, color coding should not be relied upon exclusively, but should instead be combined with some redundant coding method. For example, in the current system, flashing is used to indicate the intention to turn (one side flashes) or the presence of a hazard (both sides flash). When the running lights become brighter and a third, higher light is illuminated as well, it indicates that the brakes have been applied. These can be detected regardless of the color used. Using color as a redundant coding dimension can also provide other benefits. Redundant color coding has been found to significantly reduce search time, counting time, and counting errors. Color alone and redundant color/shape coding both produce significantly shorter response time than shape alone in visual search tasks. For visual search, counting and identification tasks, redundant color coding significantly reduces response time and error rates.
- Use no more than 10 hues (three or less preferred). More colors can be added if the saturation and brightness are varied along with the hue. In addition to the red, amber, and white already used, some designers have advocated adding a fourth color. This should not be an issue with rear-signaling systems, as designers are not advocating a large number of colors.
- Response times to colored stimuli depend on their location in the visual field. White provides the widest field of view (meaning it can be seen further into the periphery) and shortest response times for human observers, while red provides the narrowest field of view and longest response times. Blue, green, and yellow fall in between white and red both in terms of field of view and response times.
- In general, if a signal has good brightness contrast against a dark background, and if the absolute level of brightness of the signal is high, the color of the signal is of minimal importance in attracting attention. But with low signal-to-background brightness



contrast, a red signal has a marked advantage, followed by green, yellow, and white in that order.

- Color coding can be implemented in a limited space.
- Color coding is good for search tasks, probably because colors catch the eye more readily than some other forms of visual coding.
- Color coding is better for identification tasks (assigning meaning to the code) than other types of visual coding, with the exception of alphanumeric coding.
- Color coding is good for qualitative reading.
- Not all colors are equally discernible.
- Use similar colors to convey similar meanings.
- Use brightness and saturation to draw observer attention.
- Keep in mind that environmental conditions, task parameters, and individual differences can all influence the effectiveness of color coding. For rear signaling, this has implications in how well various colors can be seen in adverse weather conditions such as fog and rain. The ability to discriminate between different colors also diminishes in low ambient light conditions. The use of colored ambient lighting (e.g., sodium-vapor street lighting) can affect the perception of colors.

### Position Coding

The CHMSL is an example of a signal that is coded by its position in the center and above the two lower brake lights (except in certain models of the Chevrolet Lumina minivan, where it was positioned below the side brake lights). Traffic signals are also position coded, with red (stop) at the top, amber (caution) in the middle, and green (go) at the bottom. There are very few guidelines for the position coding of signals, as shown below.

- Regardless of stimulus color, detection is worst within a 40-80 degree arc of visual angle below the fovea, and best within a 30 degree arc from the center of the fovea.
- Peripheral vision is poor for detecting targets, especially if they are small or stationary.
- At photopic (high) illumination levels, acuity rapidly decreases as the target is displaced toward the periphery of the visual field. At low (scotopic) levels of illumination, acuity is greatest when the target is offset ~4 degrees from fixation, and acuity declines as distance increases.
- As the target angle increases, both target acquisition time and processing time increase.

### Size Coding

Many inventors have designed systems that rely on some form of size coding. In some cases, the display has two or three fixed sizes, each of which conveys a specific amount of information. In other cases, the size is continuously variable (e.g., inside-out expanding horizontal light bar), with a larger display conveying the information that the risk is greater. Guidance on the use of size for coding information is presented below.

- Use no more than five or six sizes (no more than three is preferred).
- Size coding requires a considerable amount of space.
- Use size coding only when specifically appropriate.
- Within some reasonable limits, bigger is generally better. Context plays a role with regard to size effects on salience; in other words, size as related to other information in the display is important.
- Because the size of an object on the retina varies as a function of the distance of the observer from the object, perception of size is closely related to the perception of distance.
- In a highly cluttered search field, observers can perform search tasks more quickly based on color coding than on size or shape coding.
- As the size of visual display increases, the average fixation time of each eye fixation decreases.
- The optimum size of a static display subtends 9 degrees of visual angle at the eye (with a minimum of 1 degree of visual angle).
- In larger displays, the tendency to concentrate fixations in the center of the display results in a loss of peripheral information. The larger the display, the more peripheral information may be lost.
- Under reduced viewing conditions, size and distance judgments are both strongly influenced by visual angle.

### Apparent Motion

Some researchers (notably Cohn) have advocated the use of apparent motion to capture the following driver's attention. In using apparent motion, the rate of change of size of the lead vehicle is exaggerated by using an inner to outer sequencing of lights. The theory is that an observer would rapidly perceive the brake lights as looming closer, due to the inward-to-outward sweeping visual image that enhances salience. Because the observer's M cells appear to be primarily stimulated by the luminous energy, the observer can react more rapidly to the braking action than with conventional brake lights. The use of apparent motion appears to stimulate

rapid M cell response in an observer's visual system. Apparent motion is also called stroboscopic motion. Guidelines for the use of apparent motion in design are presented below, followed by some comments on target movement.

- The perception of motion can be produced by the sequential presentation of stationary stimuli.
- The first stimulus should be presented from ~10-400 msec, followed by a pause of ~40-400 msec, followed by presentation of the second stimulus in a different location. The observer will see only one object moving from the first location to the second.
- The intensities and durations of the two stimuli, as well as their spatial and temporal separations, are all critical factors.
- Beta, or optimal, apparent motion is the smooth and continuous movement of a well-defined stimulus from one location to another; under the proper conditions, it is indistinguishable from real movement. Movement is seen when flash durations range from 5-200 msec, when temporal separations range from 10-200 msec, and at spatial separations of less than or equal to 18 degrees.
- The duration of the first stimulus is more important than that of the second.
- Both small and large (20 degree) stimuli produce less compelling apparent motion than stimuli of intermediate size.
- There are very large individual differences in the likelihood of reporting apparent motion. Quantitative thresholds for those who do report it may vary by 30%. The likelihood of reporting apparent motion is also greatly affected by observer attitude.
- The stimulus parameters of duration, intensity, and separation that result in the perception of apparent motion are related in a very complex way. For beta (optimal) apparent motion, these relationships follow Korte's Laws:
  - spatial distance ( $s$ ) increases as stimulus luminance ( $l$ ) increases, with the duration time ( $t$ ) and temporal interval ( $i$ ) held constant.
  - $s$  increases as  $i$  increases, with  $t$  and  $l$  held constant.
  - $l$  decreases as  $i$  increases, with  $t$  and  $s$  held constant.
  - $t$  decreases as  $i$  increases, with  $l$  and  $s$  held constant.
- Korte's Laws carry with them the implication that apparent motion will be seen at only certain values of the variables involved. They should be viewed as working rules.
- If the apparent motion stimuli are presented in the retinal periphery, the illusion is quite compelling. Such apparent motion may be highly effective as an attention getting mechanism.

## Target Movement

- Motion can be detected at a slower speed if a comparison, stationary object is also visible.
- It is common for the movement of a large region that surrounds a smaller object to be attributed to the object, a phenomenon called induced motion. The possibility of misattribution of motion is a concern for any situation in which one object is moving relative to another.
- Movement of the target or the observer or both decreases visual acuity.
- The ability to make visual discriminations under such conditions is called dynamic visual acuity.
- Dynamic visual acuity deteriorates rapidly as the rate of motion exceeds 60 degrees/sec.
- Dynamic visual acuity may be moderately correlated with static visual acuity.

## Flash Rate Coding

Closely related to apparent motion is flash rate coding (related because apparent motion relies upon flashes of light to produce the illusion of motion). Flash rate coding can be simple (i.e., a single flash rate in which the fact of flashing has inherent meaning) or complex (i.e., multiple flash rates, each of which have different meanings). Below are some general guidelines for using flash coding in rear-signaling design.

- Flashing signal lights are detected more quickly than steady signals when all other (background) lights are steady, but the advantage is lost if even one background light is flashing.
- If more than half the background lights are flashing, the reaction time for a flashing signal is more than 250 msec longer than for a steady signal.
- Flash rates of about 3-10 Hz (with duration at least 50 msec) have been recommended for attracting attention.
- For complex flash rate coding, no more than three flash rates should be used, and preferably no more than two flash rates.
- If the light is to be used to represent a continuous, ongoing condition, use a steady state light unless the condition is especially hazardous; continuous flashing lights can be distracting. To represent occasional emergencies or new conditions, use a flashing light.
- If the flash rates are tied to specific information, and the observer needs to interpret the information quickly, the observer may have to experience several cycles before being

able to interpret the information being transmitted, thus increasing reaction time. With very discrete flash rates and practice, reaction time might return to lower levels.

- Certain flash rates are triggers for epileptic seizures in susceptible people; the flash rate should not be in these danger zones, which differ between children and adults.
- A military standard for user-computer interface contains the following guidance on flash rate coding, and is in general agreement with the above guidelines: Flash coding shall be employed to call the user's attention to mission critical events only. No more than two flash rates shall be used. Where one rate is used, the rate shall be between 3 and 5 flashes per second. Where two rates are used, the second rate shall be less than 2 flashes per second.
- Recommendations for locomotive cab design are similar in intent: Flash coding should be used sparingly and never for text or numbers that are critical or need to be read quickly. Where readability is important, flash coding can be implemented by using a separate blinking symbol placed near the information that must be read.
- Finally, guidelines for using flash rate coding for the design of Windows operating system interfaces are also similar to those presented above: Flash coding is used only to display urgent information for user attention. No more than two levels of blinking or flashing codes shall be used. The flash rate of flash coding is 3-5 Hz with equal on/off times. For two levels of flash rate, the second is less than 2 Hz with equal on/off times. A flashing symbol is used for flash coding. A text item is not blinked. Users should be able to acknowledge the event causing the flash coding and suppress the flash if desired.

### Intensity Coding

Some designers have suggested encoding status information about the lead vehicle by varying the intensity of the rear signal lights. There are guidelines for this, as well as guidelines for the general intensity of warning lights where no intensity coding is being used.

- Use only when specifically appropriate.
- No more than three or four levels of brightness should be used (no more than two levels preferred).
- The ability to detect changes in the luminance of a target viewed against a fixed background is greater when those luminance changes are presented as luminance decreases than when they are presented as increases. The advantage of decrements over increments, although never very large, is greatest for small targets of short duration at low background intensities.
- At high levels of ambient illumination, symbol luminance must be increased to make up for the apparent color washout that can occur due to a reduced symbol to background contrast.

- Luminance ratios required for adequate reaction times are affected by both symbol size and the number of colors used.
- Weaker signals may be masked.
- The light should be at least twice as bright as the immediate background.

### Alphanumeric Coding

As can be seen in the following guidelines, if text is to be used in the rear-signaling concept, it should consist of a single, familiar, short word. It should also be visible, legible, readable, and of sufficient height to be read from the intended distance.

- Use consistent case (do not mix UPPER and lower case letters).
- Group numbers and letters together in codes (tb49 is better than t4b9).
- Use meaningful rather than arbitrary codes where possible.
- Avoid codes longer than four or five characters, especially if they need to be memorized.
- Avoid use of frequently confused character pairs (such as S-5).
- For output displays, abbreviations reduce reading time and convey information in less physical display space; however, abbreviations can become confusing to the user and negate potential performance benefits unless guidelines are followed in the creation of the abbreviations.

### Alphanumeric Text

- Characteristics include visibility, legibility, and readability:
  - Visibility - quality of a character or symbol that makes it separately visible from its surroundings.
  - Legibility - the attributes of alphanumeric characters that makes each one identifiable from others.
  - Readability - makes possible the understanding of the text once it is placed in meaningful groupings.
- Keep the literacy level of the intended observer in mind (especially important with written warnings).

## Distance Reading

- Use larger letters for poor contrast or low illumination conditions.
- Suggested letter heights in inches for 1:6 stroke width-to-height ratio:
  - 28" viewing distance           0.097"
  - 10' viewing distance           0.418"
  - 20' viewing distance           0.835"
  - 100' viewing distance         4.175"
  - 1000' viewing distance       41.75"

## Pictorial Coding

Symbols (or pictures or icons) are already heavily used in the transportation field, particularly on highway signs (✈ means airport) and in vehicle instrument panels (the image of a thermometer is used to indicate high engine temperature). Not many designers have suggested the use of symbols in rear-signaling systems, but if they were to be used, there are guidelines for designing the symbols.

- Symbols can sometimes shorten reaction time as compared to signal words, since they can be processed directly without the need for recoding.
- The objective is to design a symbol that best represents its referent (the concept or thing the symbol is supposed to represent). This depends on the strength of association of a symbol with its referent, which can depend on an already established association, or the ease of learning such an association.
- New symbols should be tested to determine the ability of a user group to recognize the symbol, match it to its intended meaning, and compare it in terms of preference to other symbols.
- Clear and stable figure to ground articulation is essential.
- A contrast boundary is preferable to a line boundary.
- A closed figure is easier to process, and should be used when possible.
- The symbol should be as simple as possible, consistent with the inclusion of necessary features.
- Symbols should be unified as much as possible. When solid and outline figures occur together, the solid figure should be within the outline figure.
- The symbol should be standardized (the same symbol is *always* associated with the same referent).

### Shape Coding

Finally, shapes can also be used to give meaning to displays. The addition of the CHMSL to the rear-signaling systems of automobiles created a triangular element figure with the points of the triangle defined by the three brake lights. This is becoming diminished by the prevalence of long, flat CHMSLs, which instead turn the shape into an isosceles trapezoid. A common shape associated with a specific meaning in transportation is the octagon, used for stop signs. Although it also relies on color and text coding, the shape itself has come to mean “stop.” The following guidelines can be used in incorporating shapes into the design of rear-signaling systems.

- Shapes can be grouped to enlarge the effective pool of symbols.
- Assign consistent shape codes for all related displays.
- Shape “names” must be learned for optimal response.
- Coordinate visual shape coding with motor control requirements.
- In a highly cluttered search field, observers can perform search tasks more quickly based on color coding than on size or shape coding.
- As many as 15 geometric shapes can be used for shape coding, although the preferred number is no more than five.
- Shapes used together need to be discriminable. Some sets of shapes are more difficult to discriminate.
- There is no statistical difference in response time to various simple shapes of warning signals. Subjective preference is for an inverted triangle.
- Shape information can be used under some conditions to enhance visual detection and may be useful as an advance cue in these conditions as well.

### **Conclusions from Literature Review**

The literature review provides a wealth of information on which to base decisions for the other subtasks of Task 1. The database review reveals that rear-end crashes are a significant problem in terms of percentage of overall crashes, injuries and fatalities, and costs. Lead vehicle stopped crashes are approximately twice as prevalent as lead vehicle moving crashes. Database analyses also show that the most common contributing factors for rear-end crashes are inattention, distraction, and following too closely.

A review of the recent history of rear-lighting initiatives shows that there have been numerous rear-lighting studies conducted over the past 35 years. These reports provide historical precedents on methods for designing, evaluating, and introducing new rear-signaling systems. However, many of the relevant scientific studies on this topic have been focused on database



analysis, laboratory testing, and simulator testing, along with a limited number of on-road experiments.

The review of the patent database and unpublished literature reveals numerous ideas for systems intended to prevent rear-end crashes. Unfortunately, few of these designs are based on accepted human factors principles, and even fewer have undergone rigorous experimental evaluation. The review of human factors guidelines demonstrates that there is an abundance of guidelines for the design of warning signals. For the most part, these guidelines have not been used in a systematic fashion to synthesize rear-lighting designs that make effective use of human perceptual processing abilities. One of the major problems is that the research has tended to focus on deceleration signals, resulting in very little information on the design and effectiveness of stopped vehicle signals.

The literature review, although thorough, leaves important topics to be addressed:

- The data showing that driver inattention and distraction are the primary contributing factors for rear-end crashes are strong, based on existing database analyses. However, in synthesizing new rear-lighting designs, we must be certain that we are addressing the correct problem (i.e., the new design must take into account the primary contributing factors and attempt to address them). The *law enforcement focus group* results presented in the next chapter help to clarify the primary contributing factors for rear-end crashes, and thus to focus the design synthesis process. Although in some sense this might be considered going back to the same well of information, there are few other sources of information as to the causes of rear-end crashes. As demonstrated in the Kostyniuk and Eby (1998) report, it can be extremely difficult to get this information directly from the driver of the striking vehicle in a rear-end crash.
- The literature review uncovered numerous inventions and ideas intended to prevent rear-end crashes, but does not provide clear guidance on which systems should be selected for further evaluation in Tasks 2 and 3. The lighting concepts appearing in the literature are not closely linked to known human detection and perception processes, nor do they directly account for the human behaviors of inattention and distraction. Thus, the burden of developing concepts that do address these issues has been left to the current project team and the team's expert panel. While use can be made of some of the concepts appearing in the literature, the concepts serve primarily as components of more comprehensive lighting configurations. The *expert panel trade study* provides this crucial guidance on concept selection.

## LAW ENFORCEMENT FOCUS GROUPS

### Goals of the Law Enforcement Focus Groups

The law enforcement focus groups were one of three major subtasks performed during Task 1. The literature review provided a database analysis perspective on the contributing factors for rear-end crashes. However, before a set of rear-lighting concepts could be presented to the expert panel for the trade study, confirmation of these contributing factors was necessary. To gain a *law enforcement perspective* on the contributing factors for and prevention of rear-end crashes, two law enforcement focus groups were conducted in the Spring of 2000. Findings from the focus groups helped increase understanding of rear-end crashes, as well as provide insight into law enforcement procedures in dealing with these crashes.

The first focus group was for officers working in an urban environment and was held in Alexandria, Virginia in February 2000. Nine officers from the Virginia State Police and the Alexandria Police Department attended this session. The second focus group was held in March 2000 in Blacksburg, Virginia with officers from the Blacksburg and Christiansburg Police Departments. Eleven officers attended the second focus group, which considered rear-end crashes in a small town/suburban environment. Each focus group lasted approximately two hours, and the officers who were off-duty were compensated for their time at a rate commensurate with non-hazardous off-duty detail pay rates. The focus group results are summarized here.

### Crash Investigation Experience

The urban focus group members had an average of 7 years of crash investigation experience, with a mean of 5.9 crashes investigated per month, of which 3.4 were rear-end crashes. The small town/suburban group averaged 9.6 years of crash investigation experience, 14.3 crashes per month, and 6.9 rear-end crashes per month. Given the years of experience, the urban group had investigated approximately 2,900 rear-end crashes over their careers, compared with 9,000 for the small town/suburban group. One major difference between the groups was the presence of Virginia State Police in the urban focus group. Those who attended primarily patrolled the northern Virginia interstate system. There tends to be a lower percentage of rear-end crashes in interstate highway driving (although as seen below, the urban focus group perceived the interstate highway to be a problem area for rear-end crashes). The estimated proportion of rear-end crashes appears to be somewhat high compared to national statistics, but the officers' estimates may have been biased by the announced purpose of the focus group. Nevertheless, there was a significant amount of experience represented in the two focus groups, both in terms of general crash investigation and in rear-end crash investigation.

### Road Type and Geometry

As far as road types where rear-end crashes occur, the two focus groups developed different rankings for problem areas, as shown below (ranked from most severe to least severe problem areas; rankings with the same number were tied):

#### Urban Focus Group

1. Interstate
2. Four-lane urban road
3. Parking lot
4. Two-lane urban
5. Commercial
5. Residential
5. Limited access (not interstate)

#### Small Town/Suburban Focus Group

1. Business district, four or more lanes
2. Construction zone
3. Business district, two-lane
4. Parking lot/private property
5. Limited access (not interstate)
6. Suburban four-lane
6. School/church zones
6. Residential

The focus groups developed the following rankings for road geometry problem areas for rear-end crashes, categorized by interstate highway, urban streets, and small town/suburban streets:

#### Interstate Highway

1. Straight section of road
2. Lane closures and work zones
3. Merge and yield zones
4. Curved section of road

#### Urban Streets

1. Intersection with traffic signal
2. Between intersections (but often related to traffic backups from intersections)
3. Intersection with stop sign
4. Merge and yield zones
5. Curved section of road without traffic signals

#### Small Town/Suburban Streets

1. Intersection with traffic signal
1. Merge and yield zones
2. Curved section of road without traffic signals
2. Human controlled intersection
3. Intersection with stop sign
3. Straight section of road without traffic signals

These rankings demonstrate that the percentage of rear-end crashes will likely vary significantly by environment, road type, and road geometry. Countermeasures for the prevention of rear-end crashes should be designed with these environmental differences in mind.

#### **Behavioral Factors in Rear-end Crashes**

With a minimum amount of prompting, officers from both groups were able to develop extensive lists of behavioral factors in rear-end crashes. The lists developed were very similar between the two groups, and included the following factors (note that these factors were unranked here, but were later ranked via individual questionnaires):

- Rubbernecking/at an crash scene or construction scene
- Adjusting the CD Player/Radio
- Dialing/talking on a cell phone
- General inattention/daydreaming
- Hurrying/driving too fast/speeding
- Error in anticipating action of lead vehicle driver
- Following too closely
- Aggressive driving
- Distracted by children/pets
- Reading
- Reaching for something in the vehicle/dropped a cigarette
- Eating/drinking
- Looking over the shoulder (side window or mirror), usually preparing to change lanes
- Fatigued/impaired by alcohol or drugs/asleep
- Talking with passenger(s)
- Applying make-up/fixing hair/shaving
- Driver lack of experience/immaturity
- Driver over-confidence with the local traffic patterns
- Driver attempting to put on seatbelt
- Looking in rear-view mirror rather than forward

### **Primary and Contributing Behavioral Factors in Rear-end Crashes**

The next phase of the focus groups investigated the ability of officers to determine the primary and contributing causes of rear-end crashes. Officers across both focus groups agreed that approximately 75% of the time drivers of the following vehicles try to shift the blame or in some way claim that the crash is not their fault. However, the officers estimated that they are able to ascertain the cause of the crash between 50% and 75% of the time using follow-up interviews

and eyewitness accounts. In any case, the following drivers are ticketed about 85% of the time with a violation of law assigned as the cause (excess speed, following too closely, reckless driving, etc.). In some cases, the officer’s priority is to get the crash cleared and get the flow of traffic moving again, so no real effort is made to delve into the cause of the crash unless it involves a serious injury or fatality.

Immediately following this session of the focus groups, officers were given a short break and asked to fill out questionnaires individually. The main purpose of the questionnaires was to get officers to rank the behavioral causes developed earlier, and to then estimate the percentage of rear-end crashes attributable to each cause. The data were analyzed in two ways: first by a simple rank sum, where the higher ranked factors for each officer received more points, and these were summed across officers; and second, by calculating the mean percentage for each factor across all officers. Since the two focus groups developed slightly different lists of behavioral factors, the top ten list is presented for each group separately, both in terms of rank sum and in terms of percentage (Tables 15-18).

**Table 15. Rank sum of behavioral causes of rear-end crashes for urban focus group (top 10).**

<b>Cause:</b>	<b>Rank sum:</b>
Driver inattention	51
Following too closely	34
Anticipating lead driver incorrectly	17
Equipment failure (such as brakes)	17
Fatigued/asleep	15
Looking elsewhere	15
Speeding	13
DWI	12
Cell phone	8
Adjusting controls	6

**Table 16. Percent of rear-end crashes attributed to behavioral causes for urban focus group (top 10).**

<b>Cause:</b>	<b>Mean%</b>
Driver inattention	44%
Following too closely	19%
Equipment failure (such as brakes)	11%
Anticipating lead driver incorrectly	6%
Fatigued/asleep	6%
Looking elsewhere	6%
Speeding	4%
Distraction	3%
Cell phone	3%
DWI	2%
Adjusting controls	2%

**Table 17. Rank sum of behavioral causes of rear-end crashes for small town/suburban focus group (top 10).**

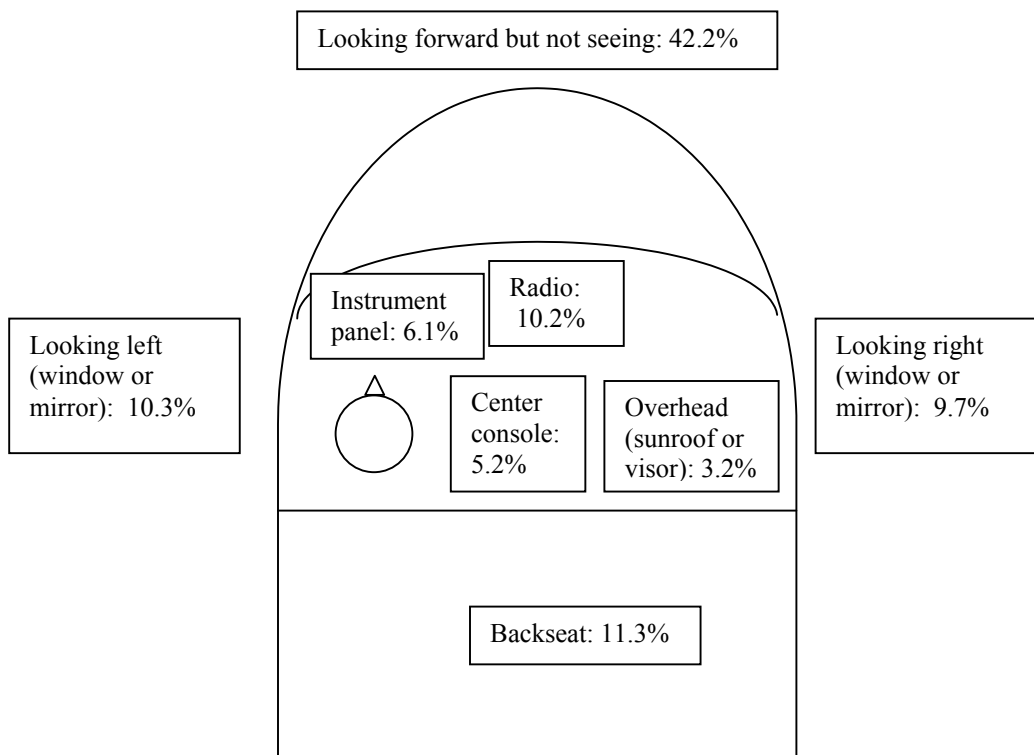
<b>Cause:</b>	<b>Rank sum:</b>
Driver inattention	59
Following too closely	35
Aggressive driving	33
Speeding	29
DWI	22
Anticipating lead driver incorrectly	19
Unfamiliar with road	11
Inexperience	10
Fatigued/asleep	9
Rubbernecking	9

**Table 18. Percent of rear-end crashes attributed to behavioral causes for small town/suburban focus group (top 10).**

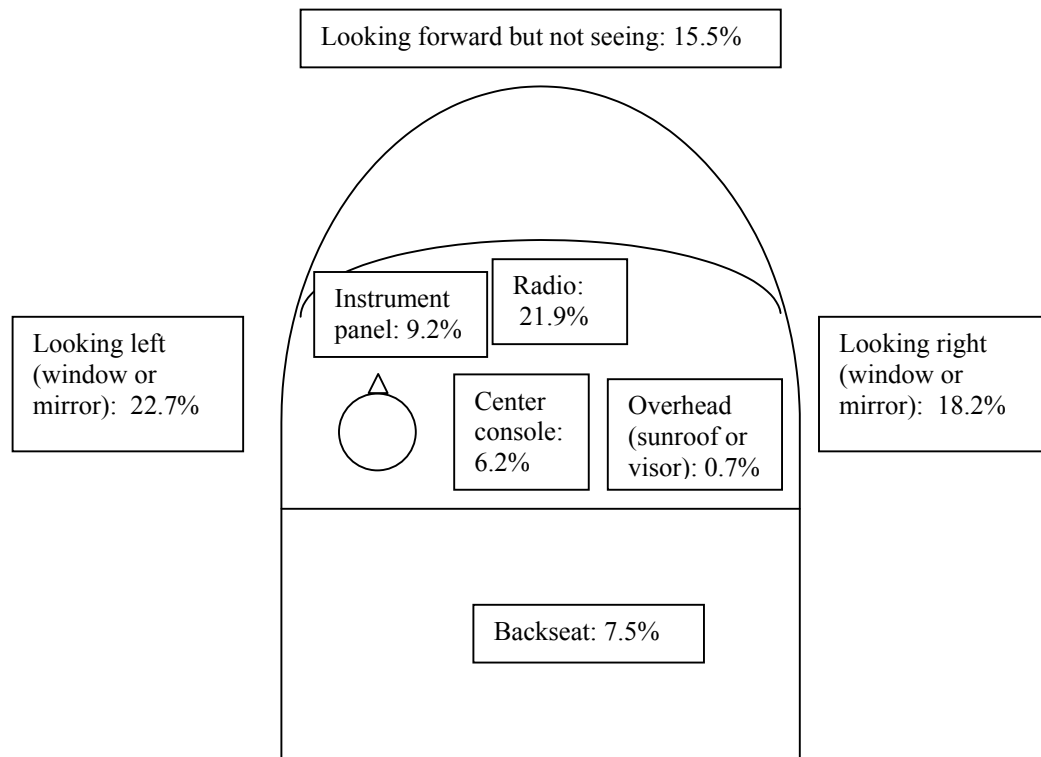
<b>Cause:</b>	<b>Mean%</b>
Driver inattention	50%
Following too closely	19%
Speeding	12%
Anticipating lead driver incorrectly	10%
Aggressive driving	10%
DWI	9%
Looking elsewhere	5%
Inexperience	4%
Rubbernecking	4%
Children/pets in car	3%
Cell phone	3%

### **Driver's Eye Behavior Immediately Prior to a Rear-end Crash**

Police officers were also asked to estimate where drivers were looking immediately prior to the rear-end crash. The results are presented in Figures 2 and 3. Note that the results differ somewhat between the two groups. The urban focus group had a much higher level of agreement on driver's eye behavior, while the small town/suburban focus group did not reach agreement on this issue. The data were obtained via questionnaire, and officers did not discuss their estimates with one another while completing them. Based on officers' verbal and written comments, the category of looking forward but not seeing seemed to relate more to inattention and daydreaming than to perceptual difficulties.



**Figure 2. Mean estimated eye behavior of following drivers at time of rear-end crash, urban focus group.**



**Figure 3. Mean estimated eye behavior of following drivers at time of rear-end crash, small town/suburban focus group.**

### **Non-Behavioral Factors in Rear-end Crashes**

After officers completed the questionnaires, the focus group was reconvened to discuss non-behavioral factors that may impact rear-end collisions. In compiling a list of non-behavioral factors, officers noted that many of them are rooted in behavioral factors. For example, mechanical failure of the brakes can often be traced to the behavioral factor of failing to perform vehicle maintenance when needed. Officers in the urban group estimated that less than 5% of rear-end crashes can be traced to non-behavioral causes, while the small town/suburban group estimated that it could be as high as 20-30%. A combined list of non-behavioral causes is presented below.

- Sun in eyes
- Brake failure
- Brake lights not working or not activated
- Wet or slick roads/road conditions/weather
- Other driver's illegal or unsafe actions (e.g., sudden lane change revealing a stopped vehicle ahead)



- Mechanical problems other than brakes and brake lights (tires, suspension, other lighting, and steering)
- Changing traffic patterns
- Medical (heart attack/seizure)
- Traffic volume
- Other crash
- Animals/deer
- Emergency vehicles
- Dirty windshield
- Visibility
- Bicyclist/pedestrians
- Obstacles/road defects

#### **Prevention of Rear-end Crashes Through Engineering Solutions**

Officers were informed that current rear vehicle lighting provides only the following information:

- Foot on brake (brake light)
- Presence (tail lights and license plate light)
- Turning (turn signal)
- Hazard present (hazard lights)
- Backing up (back-up lights)

Officers were then asked whether there was any other information that might be useful to the driver of the following vehicle, and the proceeding list was constructed (results of both focus groups combined):

- Braking intensity
- ABS activation
- Rapid deceleration, indicated by lights or an audible alert
- A vehicle-to-vehicle radar system that would provide a signal to the following driver

- Variable message signs
- Do not add anything new; instead improve driver training
- Deceleration flashers on the sides of the lead vehicle
- Reflective tape
- Distance sensor/display
- Variable intensity rear lighting (depending on ambient light)

Officers made several interesting comments and observations at this point in the focus group. One officer commented that drivers would adapt to any new design and it would not reduce the number of rear-end collisions. Some officers suggested a flashing CHMSL or perhaps even a strobe, similar to the strobe that has currently been implemented on the red traffic signal, to catch the other driver's attention. Other officers thought that only stopped vehicles should activate a strobe light, because the strobe could prove annoying in heavy traffic. One officer felt very strongly that nothing new would make any difference because drivers would get used to the new signal and the crash rates would soon return to the previous level. This officer felt that people do not take driving as seriously as they should. At least one officer thought high-end cars are less likely to be involved in a rear-end crash. Officers speculated that personality and/or status may influence driving style and crash likelihood.

One officer noted that we need to make the driving task simpler, since the biggest problem is driver inattention. Another officer speculated that since cars are better insulated than they used to be, drivers are not aware of their speed and are losing sound cues. An officer suggested that in high volume traffic, variable message signs should be used to indicate high traffic density ahead. One officer suggested the need for better driver training, including information on how ABS works and vehicle dynamics, while another stressed the need to train drivers how to drive defensively.

### **Non-Engineering Solutions for Rear-end Crashes**

Officers were then asked to rank non-engineering solutions for rear-end crashes. The urban focus group developed the following list (from most to least promising):

1. *Training solutions* should be pursued first, providing drivers with training in physics, risk analysis, stopping distance, ABS, new technology, and how to take evasive action.
2. *Engineering solutions* should be pursued with caution, and should be focused on reducing the degree of injury sustained in a crash, and not on designing new rear-lighting systems.
3. *Legislative solutions* should be pursued as a last resort, perhaps enacting new laws allowing officers to ticket for negligent vehicle maintenance (out of gas, bad tires, etc.). The main legislative solution would be for courts to enforce the laws that are currently on

the books. The problem with cell phones is in the dialing, so hands free dialing should be mandated.

4. *Other avenues* for reducing rear-end crashes include working with insurance companies, using the Virginia State Police crash database, and using videotape analysis.

The small town/suburban focus group came up with a slightly different ranking scheme:

1. *Increased enforcement* would require police officers to increase ticketing for following too closely and the courts to enforce the current laws.
2. *Legislative enforcement* suggestions included: camera monitored intersections, mandatory hands-free cell phones in vehicles, aggressive driving laws, increases in DUI penalties, increases in the number of officers patrolling the streets, creation of a traffic division in all police departments, and targeting of specific locations and particular types of violations.
3. *Better signage* for improved reminders of speed, road hazards, etc.
4. *Education* by using simulators to help demonstrate to younger drivers the impact of a 20 mph collision. They need to understand the consequences of their actions. The courts also need to be more strict with the younger drivers and assign penalties for their actions.
5. *More parental responsibility* if their children are involved in crashes.

### **Conclusions from Focus Groups**

The most significant finding from the focus groups is that law enforcement officers perceive driver inattention and distraction to be the most frequent behavioral causes for rear-end crashes. This is in accordance with findings from crash database studies, and indicates that law enforcement will most likely be supportive of measures intended to increase driver attention to the forward scene and to decrease distraction.

The officers do provide guidance on rear-signaling systems that they feel would be effective in reducing the number of rear-end crashes. However, each of the rear-signaling ideas they suggest has already been uncovered and discussed by means of the literature review. Thus, the expert panel trade study for the selection of rear-lighting configurations for further evaluation in Tasks 2 and 3 remains an important component of Task 1, and is presented in the following section.

Aside from the above main finding, the officers also caution that risk compensation may occur if rear-lighting configurations are developed. Thus, initial effectiveness may be reduced somewhat by increases in driver aggressiveness.

## EXPERT PANEL TRADE STUDY

### Goals of Expert Panel Trade Study

The focus groups provided confirmation that an effective rear-signaling system needs to attract the following driver's attention, whether the driver is in a distracted state (visual preoccupation) or simply being inattentive (mental preoccupation). The literature review provided a wealth of rear-signaling concepts and human factors guidelines for how to attract attention, but left an important question unanswered: *What are the best systems for further testing?* A trade study was conducted to accomplish this goal. An important aspect of the trade study analysis is the use of experts to help develop the criteria and to score the alternatives according to the criteria. An outstanding panel of rear-lighting experts was assembled, and they participated electronically by answering email questionnaires. Three questionnaires were used. The first questionnaire was used to create a set of criteria against which the candidate rear-signaling concepts would be judged. The second questionnaire had the experts rate the criteria according to importance to the overall goal of reducing rear-end crashes.

At this point an important juncture was reached. The experts were assembled and the criteria were ready, but there was no clear list of candidate concepts. The experts had been given the opportunity to suggest concepts during each of the first two questionnaires, but provided no ideas that were new to the researchers (after having performed the literature review). Thus the VTTI researchers were forced to devise candidate concepts, using what was known and had been learned about human perception. Given that the following driver's attention needs to be captured, there are specific methods for accomplishing this using color coding, shape coding, flash coding, size coding, and apparent motion. Use of redundant coding is also important for any warning system. The researchers used these guidelines to create a set of eight unique, redundantly coded rear-lighting concepts designed to capture the following driver's attention.

Once the concepts had been developed, the expert panel was presented with the third questionnaire in which they were asked to rate each concept according to the previously developed criteria. The ratings were then multiplied and summed according to the Kepner-Tregoe trade study procedure. As will be seen, this procedure resulted in three clearly superior candidates for further evaluation in Tasks 2 and 3.

### Expert Panel Method

The Kepner-Tregoe trade study technique was used to help determine the systems chosen for further study in Tasks 2 and 3 of this project. The Kepner-Tregoe technique is helpful when a decision must be made between two or more alternatives. (In this case, the alternatives were a set of enhanced rear-lighting concepts.) As implemented for the purposes of this project, the technique has three main steps. First, the criteria against which each alternative will be judged are developed. Second, these criteria are divided into MUSTs and WANTS, with MUSTs being those criteria that each alternative must have in order to receive further consideration, and WANTS being those attributes that are desirable for the alternatives under consideration but which are not absolutely necessary. During this second step the WANTS are also weighted according to their overall importance. In the third step, the concepts are presented to the participants, who rate them according to how well they meet the MUSTs and WANTS criteria.

In a final, in-house step, the weightings developed in step 2 are multiplied by the ratings provided by the experts in step 3 to determine which alternatives have the highest overall score (and thus best meet the criteria developed in step 1).

The Kepner-Tregoe technique is usually performed using participants who are interacting in real time and real space in a seminar-type meeting. Because of the preferences of the expert panel members, the meeting was conducted electronically for this project. Potential members were recruited via personal contacts at a rear-lighting meeting, as well as electronically. The trade study was conducted using a series of questionnaires sent to the experts as email attachments. Members then had the choice of filling out the questionnaires electronically, or printing them out, filling them out by hand, and faxing them back to VTTI. Most chose to participate totally electronically. This was a very efficient way of conducting the trade study. Panel members were allowed to perform the work at times when it was convenient to do so. The electronic method also resulted in much lower costs as compared to a meeting where the participants must travel. This method had the advantage of ensuring that the opinions obtained were independent *and* equally weighted, which is not always possible in a live meeting. Finally, this method allowed participants time to think through the issues involved and provide insightful answers to the questionnaires.

#### **Membership on the Expert Panel**

Twelve members were nominated (either self-nomination or nomination by others on the panel) and agreed to serve on the panel. There was one government representative (from a state government), five from the automobile manufacturer segment (one retired), two from academia, and four from other industries (automotive suppliers). Member experience in the field of automotive rear lighting ranged from 6 to 43 years, with a mean of 22.2 years and a grand total of 266 years. This group proved to be a highly valuable resource in helping narrow the field of candidate rear-lighting systems for further consideration, and in providing insight into the most important considerations in developing new rear-lighting systems.

#### **Questionnaire 1**

As mentioned, the first step in the Kepner-Tregoe trade study technique is to develop the criteria against which the alternatives will be judged. An initial set of criteria were developed in-house at VTTI and circulated among the human factors staff. Revisions were then made based on the input from VTTI human factors personnel. The criteria were assembled into Questionnaire 1, which was then sent to the expert panel. The criteria as sent to the expert panel in Questionnaire 1 are shown in Table 19.

**Table 19. Original criteria as presented to expert panel in Questionnaire 1.**

<b>The design is potentially beneficial because it:</b>
Addresses at least one causal factor associated with rear-end collisions. Relevant causal factors include driver inattention and following too close.
Improves driver perception of impending rear-end crashes by providing information to the following driver that a lead vehicle is stopped or slowing.
Is expected to improve conspicuity and attention-getting qualities by a statistically measurable margin over current systems.
Is unambiguous in meaning. Without training, the following driver can easily and quickly determine the meaning of the signal and take appropriate action.
Is expected to reduce rear-end collisions by more than 5%.
Is not perceived by surrounding drivers as uncomfortable or annoying considering the details of activation, particularly in heavy traffic.
Is expected to produce a measurable long-term reduction in rear-end crashes after the novelty phase has passed.
<b>The design is technically and practically sound, because it:</b>
Is compatible with present and near-future electrical systems and light technologies for automobiles.
Is not expected to require a separate power supply or extensive reworking of the electrical system design for models currently in production.
Once in mass production, is not expected to add more than \$100 to the price of an automobile.
Is expected to be economically justifiable when the expected cost is balanced against the expected benefits.
Is compatible with existing FMVSS rear lighting standards, or would likely pass rulemaking exercises.
Is likely to find support at the national and international levels among committees working on automotive signaling and lighting.
Could easily be incorporated into current vehicle styling with regard to color, size, and position. Would not be likely to provoke opposition from automobile designers/stylists.
The transition period of equipping vehicles would be expected to proceed with a minimum of delays and problems. The infrastructure for producing the technology is in place and could go into mass production with a few months notice.
Is compatible with truck and bus signal systems in terms of technology and ease of understanding. Truck and bus drivers would not be likely to object to the new system on the basis of how they would perceive the new system due to their higher vantage point.
Is expected to have at least the same level of reliability (mean time between failure) as current rear signaling systems.
<b>The design has the following performance characteristics:</b>
Utilizes sufficient intensity/intensities based upon previous research and sound human factors principles. The intensity/intensities is/are sufficient for all common driving conditions such as night, day, dawn, dusk, rainy, cloudy, sunshine, and fog.
Utilizes color(s) that is (are) meaningful and attract(s) attention (if applicable to the system under consideration).
Is of adequate size to be recognized from the intended distance. Note that the intended distance may vary with the design.
Is placed so as to optimize the driver's ability to detect the cue. For visual cues, this would suggest that the system is at the following driver's eye-level; for auditory cues, the system should be placed in the interior of the following vehicle, as exterior auditory cues would be expected to have a high annoyance rating.
Operates in such a way that the following driver has adequate time to perceive and react to the cue(s). Takes human perception/reaction time into account.

Experts were asked to recommend whether each criterion should be kept or dropped, and to suggest changes to the criteria. They were asked to suggest new criteria in areas they felt were lacking, and to suggest novel rear-lighting concepts for possible use later in the trade study. Eight experts replied to Questionnaire 1 within the specified time frame, and their input led to

the development of the final criteria. Of the original list of criteria, some were dropped, some were modified, some were split into two criteria, and new criteria were added. The resulting list was used in Questionnaire 2, where the MUSTs and WANTS were evaluated.

### **Questionnaire 2**

The finalized list of criteria was sent to the expert panel, who were asked to decide whether each criterion should be a MUST or a WANT. For each WANT, the experts were asked to rank the criterion from 1 to 10 in terms of its importance. Experts were also allowed to make final comments on the criteria, and were provided with another opportunity for suggesting re-orienting concepts for consideration in later stages of the process. Eleven expert panel members responded to Questionnaire 2. The criteria they were asked to evaluate in Questionnaire 2 are presented in Table 20.

The answers received from the experts resulted in further minor modifications to the criteria. Three of them were dropped because of their relatively low importance ratings. A few others were slightly reworded. The final list of criteria, along with the mean ratings provided by the experts, can be found in Table 21. An *a priori* cutoff of 80% was selected for inclusion in the MUST category. In other words, if more than 80% of the respondents rated the criterion as a MUST, then it was placed in the MUST category, otherwise it was placed in the WANT category. For those experts who rated a criterion as a MUST, but the criterion ended up as a WANT, their weighting for that criterion was assigned as a 12 (i.e., more important than the highest WANT weighting) for purposes of calculating the mean weightings. This procedure resulted in some mean criterion weightings that were greater than 10, as can be seen in Table 21.

**Table 20. List of criteria as sent to expert panel in Questionnaire 2.**

<b>THE DESIGN IS POTENTIALLY BENEFICIAL BECAUSE IT:</b>
Addresses at least one causal factor associated with rear-end collisions. Relevant causal factors include driver inattention, driver misperception, and following too closely.
Improves driver perception of impending rear-end crashes by providing information to the following driver that a lead vehicle is stopped or moving slowly.
Is expected to improve conspicuity and attention-getting qualities by a statistically measurable margin as compared to a representative current system.
Without training, the following driver can easily and quickly determine the meaning of the signal and take appropriate action. (The signal is unambiguous in meaning.)
Is expected to produce a measurable long-term reduction in rear-end crashes after the novelty phase has passed. Is expected to be at least as successful as the CHMSL, which has a long-term effectiveness of approximately 4%.
Is not perceived by the <i>following</i> driver as uncomfortable or annoying when no rear-end collision is imminent (e.g., when stopped in traffic at a traffic signal).
Is not perceived by <i>surrounding</i> (versus following) drivers as uncomfortable or annoying considering the details of activation, particularly in heavy traffic.
Operates in such a way that the following driver has adequate time to perceive and react to the cue(s) in most driving conditions at the necessary distances. Takes human perception/reaction time into account.
When implemented, the new design does not reduce the effectiveness of existing rear signaling systems (including directional and stop signals). If the CHMSL is replaced in the new design, the effectiveness is expected to be superior for the new system.
<b>The design is technically and practically sound, because it:</b>
Is compatible with present and near-future electrical systems and light technologies for automobiles.
Is not expected to require a separate power supply or extensive reworking of the electrical system design for models currently in production.
Is expected to be economically justifiable when the expected cost is balanced against the expected benefits. (Final design justification would include a cost benefit analysis.)
Would likely pass FMVSS rulemaking exercises for rear lighting standards.
Is likely to find support at the national and international levels among committees working on automotive signaling and lighting.
Could easily be incorporated into current and near-future vehicle styling trends with regard to color, size, and position.
Is compatible with truck and bus signal systems in terms of technology and ease of understanding. Truck, bus, and other high-profile vehicle drivers would not be likely to object to the new system on the basis of how they would perceive the new system due to their higher vantage point.
Is expected to have nearly the same level of reliability (mean time between failure) as current rear signaling systems, over the expected lifetime of the vehicle.
<b>The design has the following design characteristics:</b>
Utilizes sufficient intensity/intensities based upon previous research and sound human factors principles. The intensity/intensities is/are sufficient for all common driving conditions such as night, day, dawn, dusk, rainy, cloudy, sunshine, and fog.
Utilizes color(s) effectively and attract(s) attention (if applicable to the system under consideration).
Is of adequate size to be recognized from the intended distance. Note that the intended distance may vary with the design.
Is placed so as to optimize the driver's ability to detect the cue, taking sensory modality into account.



**Table 21. Final list of criteria and ratings based on results of Questionnaire 2.**

<b>The design is potentially beneficial because it:</b>	<b>Rating</b>
Addresses at least one causal factor associated with rear-end collisions. Relevant causal factors include driver inattention, driver misperception, and following too closely.	MUST
When implemented, the new design does not reduce the effectiveness of existing rear signaling systems (including directional and stop signals). If the CHMSL is replaced in the new design, the effectiveness is expected to be superior for the new system.	WANT, 11.0
Improves driver perception of impending rear-end crashes by providing information to the following driver that a lead vehicle is stopped or moving slowly.	WANT, 10.9
Operates in such a way that the following driver has adequate time to perceive and react to the cue(s) in most driving conditions at the necessary distances. Takes human perception/reaction time into account.	WANT, 10.4
Is expected to improve conspicuity and attention-getting qualities by a statistically measurable margin as compared to a representative current system.	WANT, 9.4
Without training, the following driver can easily and quickly determine the meaning of the signal and take appropriate action. (The signal is unambiguous in meaning.)	WANT, 9.4
Is expected to produce a measurable long-term reduction in rear-end crashes after the novelty phase has passed. Is expected to be at least as successful as the CHMSL, which has a long-term effectiveness of approximately 4%.	WANT, 9.4
Is not perceived by <i>surrounding</i> (versus following) drivers as uncomfortable or annoying considering the details of activation, particularly in heavy traffic.	WANT, 7.4
Is not perceived by the <i>following</i> driver as uncomfortable or annoying when no rear-end collision is imminent (e.g., when stopped in traffic at a traffic signal).	WANT, 7.2
<b>The design is technically and practically sound, because it:</b>	<b>Rating</b>
Is expected to be economically justifiable when the expected cost is balanced against the expected benefits. (Final design justification would include a cost benefit analysis.)	WANT, 9.0
Would likely pass FMVSS rulemaking exercises for rear lighting standards.	WANT, 8.9
Is expected to have nearly the same level of reliability (mean time between failure) as current rear signaling systems, over the expected lifetime of the vehicle.	WANT, 8.2
Is not expected to require a separate power supply or extensive reworking of the electrical system design for models currently in production.	WANT, 8.1
Is compatible with truck and bus signal systems in terms of technology and ease of understanding. Truck, bus, and other high-profile vehicle drivers would not be likely to object to the new system on the basis of how they would perceive the new system due to their higher vantage point.	WANT, 7.1
<b>The design has the following design characteristics:</b>	<b>Rating</b>
Utilizes sufficient intensity/intensities based upon previous research and sound human factors principles. The intensity/intensities is/are sufficient for all common driving conditions such as night, day, dawn, dusk, rainy, cloudy, sunshine, and fog.	WANT, 10.3
Is of adequate size to be recognized from the intended distance. Note that the intended distance may vary with the design.	WANT, 9.0
Is placed so as to optimize the driver's ability to detect the cue, taking sensory modality into account.	WANT, 8.5

### Questionnaire 3

Prior to Questionnaire 3, VTTI personnel developed a set of enhanced rear-lighting concepts. These concepts were developed after reviewing a variety of sources including literature, patent searches, and ideas provided by the expert panel, although the majority were a result of in-house concept generation. Each concept was developed to include a description, a justification, implementation details, activation criteria, deactivation criteria, and a graphic representation. In all, eight concepts were developed, five of which were closed-loop systems and three of which were open-loop systems (definitions of open- and closed-loop systems are provided in the next subsection).

Since there was no earlier single concept or group of concepts suitable for testing without extensive modifications, rear-lighting concepts were developed/assembled using sound human factors principles. Certain previous ideas were borrowed and integrated into the newly evolved lighting *systems*. There is an extensive body of literature providing guidelines for developing effective warning displays using various forms of coding (these were described in the literature review).

An additional consideration in candidate lighting system development was that of redundancy. By combining concepts, it would be possible to take advantage of multiple cues, any one or more of which might attract the following driver's attention. The problem with redundant cues is that there would be insufficient resources to study individual aspects factorially. Thus, lighting systems might be found effective or ineffective in experimentation, but it would not be possible to tell which aspect or aspects were providing the greatest effectiveness. Nevertheless, with the resources available, it was felt that maximum emphasis should be placed on optimizing and testing the most promising concepts, and that factorial evaluation, except in the post hoc comparisons, would not be feasible. The following sections provide an overview of the contents of Questionnaire 3, including definitions of open- and closed-loop systems, followed by concept descriptions and then activation/deactivation criteria.

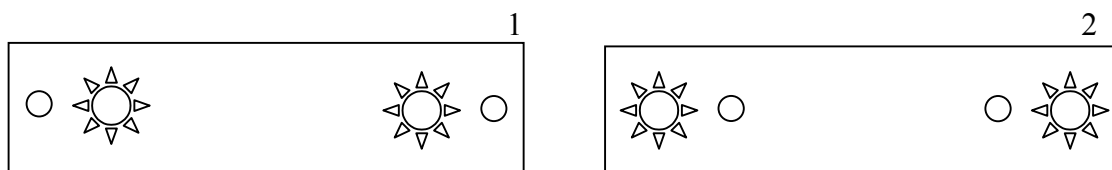
#### Closed-loop and Open-loop Systems

*Closed-loop system.* In this type of system, a detector (most likely radar based) is placed on either the rear bumper of the lead vehicle or the front bumper of the following vehicle. By measuring headway, closing rate, and possibly angle, a signal can be presented either on the rear of the lead vehicle or inside the passenger compartment of the following vehicle (or both) whenever the headway is too short or the closing rate is too high. If the signal is presented inside the following vehicle, it could be auditory, visual, or both. One advantage of a closed-loop system is that when the criteria for impending collision no longer exist, the system can be deactivated (e.g., both vehicles have stopped, so the closing rate drops to zero for some predetermined amount of time and the signal is deactivated). This has the advantage of reducing annoyance in heavy traffic situations. Most importantly, closed-loop systems are capable of precise determination of impending rear-end collisions. Note that the scope of this work included only the closed-loop system in which the system is fully contained within the lead vehicle. However, the closed-loop system where the system is contained within the following vehicle was also included in the trade study, since it is a logical extension of some of the collision avoidance and intelligent cruise control research currently being conducted. It was included only as a control condition for soliciting expert opinion on how the two types of closed-loop systems compare.

*Open-loop system.* In this type of system, the lead vehicle displays a signal of some sort, based on a predetermined parameter (or set of parameters) such as degree of deceleration, and the driver of the following vehicle must perceive the signal and respond appropriately. There is no feedback loop between the vehicles (thus open-loop). To avoid auditory “noise pollution,” this signal would most likely be visual. Also, in many cases the signal would remain activated as long as the parameter or parameters of interest are in the predetermined mode. For example, if the signal is a stopped vehicle signal, the signal would remain activated until the vehicle is moving again (although there is the possibility of timing out the open-loop activation). If the signaling system is not timed out, a lower intensity signal might be required to diminish glare, annoyance, and light adaptation problems. In an open-loop system, a complex trade-off exists between encompassing the majority of rear-end crash scenarios on the one hand, and avoiding false alarms and annoyance on the other hand. The two-stage system with a time-out feature described for the open-loop systems (in the activation/deactivation criteria sections) represents an attempt to optimize this trade-off.

Concept Descriptions (as presented to the expert panel)

*Concept #1, Closed-loop, Radar Activated High-Intensity Strobe Lights.* The rear of the lead vehicle would be fitted with rear-directed radar. The radar would detect the range, range-rate, and angle of the following vehicle. These variables would be used to calculate required stopping distance, taking into account driver perception-reaction time and braking distance. When minimum stopping distance is detected (i.e., a rear-end collision is imminent), four high-intensity strobe lights would be activated. These would be located in a horizontal array at the rear of the lead vehicle, with a gap in the middle clearly separating the left and right side strobe pairs. The two inner strobes would flash first, followed by the two outer strobes. A short time gap would follow the outer strobe activation, then the cycle would repeat. When stopping distance is no longer at or below minimum, the system would deactivate. Concept 1 is illustrated in Figure 4. When activation criteria are met, the inner strobes would flash once (1), followed immediately by the outer strobes (2). After a short time gap the cycle would repeat until the deactivation criteria are met.

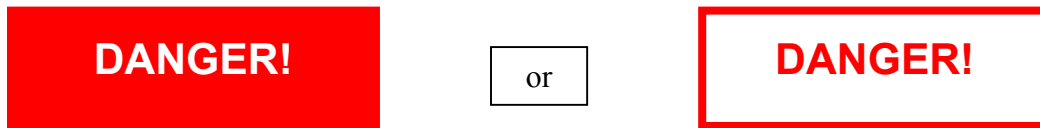


**Figure 4. Closed-loop, radar activated high-intensity strobe lights (Concept #1).**

*Concept #2, Closed-loop, Radar Activated Auditory and Visual Display in Following Vehicle.* In the simplest configuration, a forward directed radar would be fitted at the front of the following vehicle. The radar would be used to detect the range, range rate, and angle to the lead vehicle. These variables would be used to calculate the required stopping distance, taking into account driver perception-reaction time and braking distance. When minimum stopping distance is detected (i.e., a rear-end collision is imminent) both an auditory and a visual warning would be presented inside the following vehicle. The word DANGER!, presented in clear or white letters

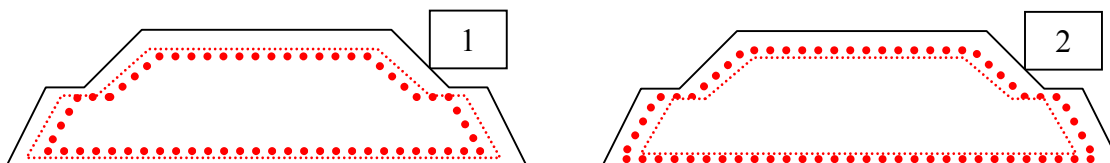
on a red background (left) or red letters on a white or clear background within a text box (right), would flash at a high rate (between 5 and 10 flashes per second) in a head-up display whenever the activation criteria are met (Figure 5). The auditory display would consist of one of the following: the word DANGER! presented in an urgent voice or the sound of a brake squeal/screech. The auditory display would repeat at short intervals, while the visual display would flash at a high rate, that is, between five and ten times per second. When stopping distance is no longer at or below minimum, the system would deactivate.

Note that the scope of the current project included only the closed-loop system in which the system is fully contained within the lead vehicle. However, the closed-loop system where the system is contained within the following vehicle was also included in the trade study, since it is a logical extension of some of the collision avoidance and intelligent cruise control research currently being conducted. It was included only as a control condition for soliciting expert opinion on how the two types of closed-loop systems compare.



**Figure 5. Closed-loop, radar activated auditory and visual display in following vehicle (Concept #2).**

*Concept #3A, Closed-loop, Radar Activated Contour Lighting.* The rear of the lead vehicle would be fitted with a rear-directed radar. The radar would detect the range, range-rate, and angle to the following vehicle. These variables would be used to calculate required stopping distance, taking into account driver perception-reaction time and braking distance. When minimum stopping distance is detected (i.e., a rear-end collision is imminent), contour or strip lighting on the rear of the lead vehicle would be activated and would flash rapidly. As shown in Figure 6, there would be two rows of red or yellow contour lighting. The inner row would flash first (1), followed by the outer row (2). A short time gap would follow the outer contour activation, then the cycle would repeat. When stopping distance is no longer at or below minimum, the system would deactivate.

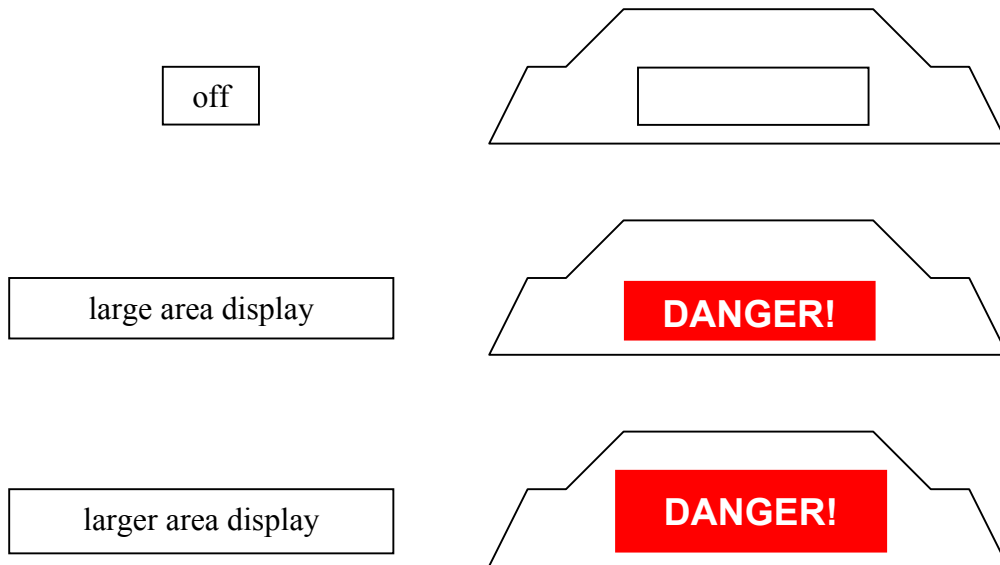


**Figure 6. Closed-loop, radar activated contour lighting (Concepts #3A and #3B).**

*Concept #3B, Open-loop, Contour Lighting Activated by Applied Brake Pedal Force.* When the brakes are applied in the lead vehicle, a row of contour or strip lighting on the rear of the lead vehicle would be illuminated continuously. If the applied brake pedal force exceeds a predetermined level, the system would enter a flashing mode. There would be two rows of red or yellow contour lighting, and the inner row would flash first, followed by the outer row. A short time gap would follow the outer contour activation, then the cycle would repeat. When the predetermined brake force is no longer present and a specified time interval has passed, the display would revert to the continuous mode if the brakes are still applied, or extinguish if the brakes are no longer applied. Refer back to Figure 6 for the graphic representation of this concept.

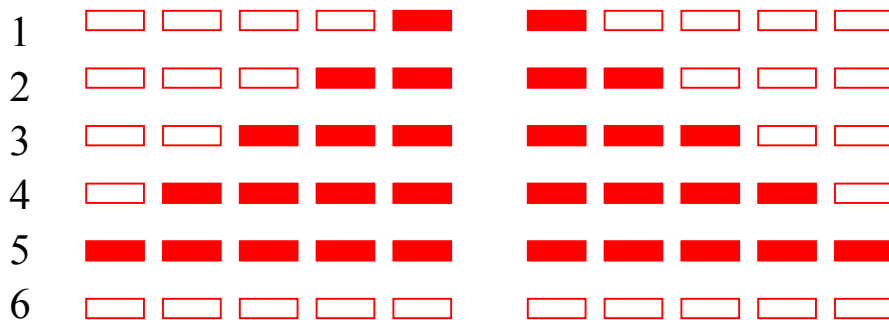
*Concept #4A, Closed-loop, Radar Activated Large Area Display.* The rear of the lead vehicle would be fitted with a rear-directed radar. The radar would detect the range, range-rate, and angle to the following vehicle. These variables would be used to calculate required stopping distance, taking into account driver perception-reaction time and braking distance. When minimum stopping distance is detected (i.e., a rear-end collision is imminent), a large area display on the rear of the lead vehicle would flash rapidly (Figure 7). The display would consist of a large (a preliminary estimate of size is 8" high by 34" wide) red or yellow light array or lighted flat panel. Immediately after the display activates, a border would be added, increasing its size (estimated at 1" all around, for a total display size of 10" high by 36" wide). The display would then extinguish for a brief period, and the cycle would begin again. The word DANGER! (unlighted) would also be contained in the display. When stopping distance is no longer at or below minimum, the system would deactivate.

*Concept #4B, Open-loop, Large Area Display Activated by Applied Brake Pedal Force.* When the brakes are applied in the lead vehicle, a large area display on the rear of the lead vehicle would be illuminated continuously. The display would consist of a large red or yellow light array or lighted flat panel (a preliminary estimate of size is 8" by 34") containing a signal word (CAUTION!) comprised of dark letters on an illuminated background. If the applied brake pedal force exceeds a predetermined level, the display would flash and a contiguous border of the same luminance would be illuminated in sequence (the border is estimated at 1" all around for a total display size of 10" high by 36" wide). The display would then extinguish for a brief period and the cycle would repeat. When the predetermined brake force is no longer present and a specified time interval has passed, the display would revert to the continuous mode if the brakes are still applied, or extinguish if the brakes are no longer applied (see Figure 7).



**Figure 7. Closed-loop, radar activated large area display (Concepts #4A and #4B).**

*Concept #5A, Closed-loop, Radar Activated Horizontal Array of Lights.* The rear of the lead vehicle would be fitted with a rear-directed radar. The radar would detect the range, range-rate, and angle to the following vehicle. These variables would be used to calculate required stopping distance, taking into account driver perception-reaction time and braking distance. When minimum stopping distance is detected (i.e., a rear-end collision is imminent), a horizontal array of lights on the rear of the lead vehicle would repeatedly spread outward from the center. As shown in Figure 8, the innermost pair of lights would activate (1), followed in quick succession by the other pairs (2-4) until the entire horizontal array is lit (5). The lights would then extinguish briefly (6) and the cycle would repeat until the deactivation criteria are met. These lights could be red or yellow in color. When stopping distance is no longer at or below minimum, the system would deactivate.



**Figure 8. Closed-loop, radar activated horizontal array of lights (Concepts #5A and #5B).**

*Concept #5B, Open-loop, Horizontal Array of Lights Activated by Applied Brake Pedal Force.* When the brakes are applied in the lead vehicle, a horizontal array of lights on the rear of the lead vehicle would be illuminated continuously (see Figure 8, line 5). If the applied brake pedal force exceeds a predetermined level, the lights would repeatedly activate outward from the center (Figure 8, lines 1-5). These lights would be red or yellow in color. When the predetermined brake force is no longer present and a specified time interval has passed, the display would revert to the continuous mode if the brakes are still applied, or extinguish if the brakes are no longer applied (Figure 8, line 6).

#### Activation Criteria

*Closed-loop Activation Criteria.* An algorithm for the required minimum separation to avoid a collision has been developed at VTTI, and this would be programmed into the radar-based system. When the separation approaches this minimum, the rear-lighting system would be activated. The algorithm is robust over varying speeds of the lead and following vehicles, works for the lead vehicle stopped situation, and includes an allowance for driver perception-reaction time and the coefficient of friction of the tires. More details on this algorithm can be found in the section on “Algorithms for Activation and Deactivation of Rear-signaling Concepts” later in this report.

*Open-loop Activation Criteria.* The threshold for the applied pedal force or brake-line pressure required to trigger the flashing display would be developed and programmed into the system. It would be based on moderately rapid deceleration at a specific test speed. Whenever the force/pressure reaches threshold, the rear-lighting system would begin flashing. This force or pressure activation method has advantages. First, it would signal the following driver of moderate or high deceleration of the lead vehicle. Second, if the driver of the *lead* vehicle perceives a following vehicle approaching rapidly, the system could be activated with a moderately strong pulse of brake application even though the lead vehicle is moving slowly or standing still. Thus, the driver of the lead vehicle is given some control over the situation. The display would be lit continuously whenever the driver applies the brakes (the same criterion as is currently used to activate the CHMSL), but the brake pressure criterion would override the brake application criterion. In other words, if the driver’s foot is on the brake pedal in a normal manner, the display would be lit continuously. If the driver then applies heavy brake pressure that exceeds the threshold for the applied pedal force or brake-line pressure, the display would begin flashing and would remain flashing until the deactivation criteria are met. More details on this algorithm can be found in the section on “Algorithms for Activation and Deactivation of Rear-signaling Concepts” later in this report.

#### Deactivation Criteria

*Closed-loop Deactivation Criteria.* When the criteria for imminent rear-end collision are no longer met, the system would deactivate. Thus, potential annoyance (and false triggering) would be minimized. It would be expected that the system would not trigger for traffic stopped at a traffic signal or stop sign (the cases most likely to create annoyance and glare), unless a vehicle approaches from the rear and is in danger of colliding with the stopped vehicle.

*Open-loop Deactivation Criteria.* Once the brake force/line pressure activation criterion is no longer met (i.e., the value falls below the set point), the rear-end signal would *not* stop flashing

immediately. Instead, the flashing would remain activated for a specified additional time period. This time is estimated to be 4 seconds, but would be determined by experimentation. In other words, the flashing display would be “timed-out” after brake force/line pressure falls below threshold. This timing-out feature is intended to cover likely rear-end crash scenarios in which the following vehicle approaches the lead vehicle shortly after the heavy brake application. During this time interval, the lead vehicle may still be stopped or moving slowly. The time length for timing-out represents a tradeoff between alerting the following driver and annoyance/false alarm aspects. For normal brake application, the continuous display would be extinguished either by lifting the foot from the brake pedal or by an override to the flashing mode resulting from heavy brake application.

### **Questionnaire 3 Results**

Eight expert panel members responded to Questionnaire 3. Prior to distribution, this was considered to be the minimum number of responses received before final results were tabulated (in order to obtain a representative sampling from the twelve expert panel members). The experts who returned Questionnaire 3 were quite experienced in the subject of rear lighting (mean experience = 23.5 years). Although a greater number of responses would have been desirable, the time investment required to respond to Questionnaire 3 was substantial, and so it is understandable that some people may not have had time to respond. However, the quality of responses was extraordinarily high, and it was apparent that everyone who submitted a response put considerable effort into doing so.

As the results were received, they were entered into a spreadsheet. After all eight responses were in hand, a spreadsheet was developed for each concept so that relevant statistics could be determined for each criterion/concept combination (e.g., mean, median, standard deviation). Next, a summary spreadsheet was developed in which the mean for each concept/criterion rating was entered next to the criterion rating (developed from the results of Questionnaire 2). The two ratings were multiplied, and then the sum of these products was calculated for each concept. A partial example of this spreadsheet is shown in Table 22 for Concept 1.

A shorter summary spreadsheet was then developed to present the overall results for the sum of products for all concepts, and this is presented as Table 23. Product rankings were then determined (Table 24). Other items of interest were also noted, such as the mean sum of products for the closed-loop systems and the mean sum of products for the open-loop systems. These are displayed in Table 25.

As prescribed by the KTA procedure, sensitivity analyses were then performed. To account for any effect of the distribution of the expert ratings on the results, the procedures described earlier were again followed, but using the median ratings instead of the means. In using the medians instead of the means, the intent was to discount the effect of any extreme value in rating. In other words, if one or more of the experts had a particular extreme like or dislike and rated accordingly, the median value would account for this but would not be dominated by it. The results of these analyses can be found in Tables 26 through 28.

A second sensitivity analysis method was also developed. In this method, the median was again used. However, for those systems in which the experts indicated that the system did not meet the



MUST criterion, zero values were assigned for each individual WANT criterion. (It will be recalled that any expert who made the decision that the MUST criterion was not met did not complete the WANT ratings for that concept.) It could be assumed that such experts would have rated these systems at values below the group median for those who did rate them. By setting these assigned scores to zero, the effect was to lower the median score in the ranking by one rank interval for each zero. The reason for using this third method was to have a median value that included the opinion of all eight experts. The results of this third method can be found in Tables 29 to 31.

The three methods of tabulating results produced similar results, as can be seen in the overall summary in Table 32. All three sets of results were used to create a final ranking scheme (in the second to last column of Table 32). Note that a natural break point occurred between the fourth and fifth highest ranking systems, both in terms of rank sum (a five point spread) and percentage agreeing that the system meets the MUST criterion (which dropped from 87.5% to 75% at this point). The discussion of these results follows Table 32.

**Table 22. Abbreviated summary spreadsheet example for Concept 1 (note that this is a partial reproduction of the full table).**

<b>CRITERIA:</b>	<b>Concept 1 Closed-loop, Radar Activated High-Intensity Strobe Lights</b>		
	<b>Mean</b>	<b>Criterion Rating</b>	<b>Product</b>
<b>WANT CRITERIA</b>			
<b>The design is potentially beneficial because it:</b>			
When implemented, the new design does not reduce the effectiveness of existing rear signaling systems (including directional and stop signals). If the CHMSL is replaced in the new design, the effectiveness is expected to be superior for the new system. WANT.	6.57	11	72.29
Improves driver perception of impending rear-end crashes by providing information to the following driver that a lead vehicle is stopped or moving slowly. WANT.	5.43	10.9	59.17
Operates in such a way that the following driver has adequate time to perceive and react to the cue(s) in most driving conditions at the necessary distances. Takes human perception/reaction time into account. WANT.	8.00	10.4	83.20
Is expected to improve conspicuity and attention-getting qualities by a statistically measurable margin as compared to a representative current system. WANT.	7.43	9.4	69.83
Without training, the following driver can easily and quickly determine the meaning of the signal and take appropriate action. (The signal is unambiguous in meaning.) WANT.	6.86	9.4	64.46
Is not perceived by surrounding (versus following) drivers as uncomfortable or annoying considering the details of activation, particularly in heavy traffic. WANT.	4.67	7.4	34.53

**Table 23. Summary table for expert ratings of rear-lighting concepts using mean results.**

<b>Concept Description</b>	<b>Overall Rating (sum of products of mean x criteria rating)</b>	<b>Percent agreeing that concept meets MUST criterion</b>
<b>Concept 1</b> Closed-loop, Radar Activated High-Intensity Strobe Lights	976.96	87.5%
<b>Concept 2</b> Closed-loop, Radar Activated Auditory and Visual Display in Following Vehicle	971.59	87.5%
<b>Concept 3A</b> Closed-loop, Radar Activated Contour Lighting	974.05	75.0%
<b>Concept 3B</b> Open-loop, Contour Lighting Activated by Two Levels of Braking	928.78	75.0%
<b>Concept 4A</b> Closed-loop, Radar Activated Large Area Display	951.59	87.5%
<b>Concept 4B</b> Open-loop, Large Area Display Activated by Two Levels of Braking	911.21	87.5%
<b>Concept 5A</b> Closed-loop, Radar Activated Horizontal Array of Lights	1022.25	100.0%
<b>Concept 5B</b> Open-loop, Horizontal Array of Lights Activated by Two Levels of Braking	985.74	100.0%

**Table 24. Rank order of systems for product sum using means.**

<b>Rank order</b>	<b>System</b>	<b>Product Sum</b>
1	5A	1022.25
2	5B	985.74
3	1	976.96
4	3A	974.05
5	2	971.59
6	4A	951.59
7	3B	928.78
8	4B	911.21

**Table 25. Items of interest for product sum using means.**

<b>Items of interest:</b>	<b>Product sum</b>
Top rated system: 5A	1022.25
Lowest rated system: 4B	911.21
Range between top-lowest	111.03
Mean for open-loop systems	941.91
Mean for closed-loop systems	979.29
Top rated open-loop system: 5B	985.74
Top rated closed-loop system: 5A	1022.25

**Table 26. Summary table for expert ratings of rear-lighting concepts using median results.**

<b>Concept Description</b>	<b>Overall Rating (sum of products of median x criteria rating)</b>	<b>Percent agreeing that concept meets MUST criterion</b>
<b>Concept 1</b> Closed-loop, Radar Activated High-Intensity Strobe Lights	1032.10	87.5%
<b>Concept 2</b> Closed-loop, Radar Activated Auditory and Visual Display in Following Vehicle	1051.35	87.5%
<b>Concept 3A</b> Closed-loop, Radar Activated Contour Lighting	1006.10	75.0%
<b>Concept 3B</b> Open-loop, Contour Lighting Activated by Two Levels of Braking	985.50	75.0%
<b>Concept 4A</b> Closed-loop, Radar Activated Large Area Display	999.20	87.5%
<b>Concept 4B</b> Open-loop, Large Area Display Activated by Two Levels of Braking	986.90	87.5%
<b>Concept 5A</b> Closed-loop, Radar Activated Horizontal Array of Lights	1044.60	100.0%
<b>Concept 5B</b> Open-loop, Horizontal Array of Lights Activated by Two Levels of Braking	1033.63	100.0%

**Table 27. Rank order of systems for product sum using medians.**

<b>Rank order</b>	<b>System</b>	<b>Product Sum</b>
1	2	1051.35
2	5A	1044.60
3	5B	1033.63
4	1	1032.10
5	3A	1006.10
6	4A	999.20
7	4B	986.90
8	3B	985.50

**Table 28. Items of interest for product sum using medians.**

<b>Items of interest:</b>	<b>Product sum</b>
Top rated system: 2	1051.35
Lowest rated system: 3B	985.50
Range between top-lowest	65.85
Mean for open-loop systems	1002.01
Mean for closed-loop systems	1026.67
Top rated open-loop system: 5B	1033.63
Top rated closed-loop system: 2	1051.35

**Table 29. Summary table for expert ratings of rear-lighting concepts using median results, zero values included.**

<b>Concept Description</b>	<b>Overall Rating (sum of products of median x criteria rating)</b>	<b>Percent agreeing that concept meets MUST criterion</b>
<b>Concept 1</b> Closed-loop, Radar Activated High-Intensity Strobe Lights	966.98	87.5%
<b>Concept 2</b> Closed-loop, Radar Activated Auditory and Visual Display in Following Vehicle	987.55	87.5%
<b>Concept 3A</b> Closed-loop, Radar Activated Contour Lighting	904.28	75.0%
<b>Concept 3B</b> Open-loop, Contour Lighting Activated by Two Levels of Braking	841.70	75.0%
<b>Concept 4A</b> Closed-loop, Radar Activated Large Area Display	963.18	87.5%
<b>Concept 4B</b> Open-loop, Large Area Display Activated by Two Levels of Braking	945.75	87.5%
<b>Concept 5A</b> Closed-loop, Radar Activated Horizontal Array of Lights	1044.60	100.0%
<b>Concept 5B</b> Open-loop, Horizontal Array of Lights Activated by Two Levels of Braking	1033.63	100.0%

**Table 30. Rank order of systems for product sum using medians, zero values included.**

<b>Rank order</b>	<b>System</b>	<b>Product Sum</b>
1	5A	1044.60
2	5B	1033.63
3	2	987.55
4	1	966.98
5	4A	963.18
6	4B	945.75
7	3A	904.28
8	3B	841.70

**Table 31. Items of interest for product sum using median, zero values included.**

<b>Items of interest:</b>	<b>Product sum</b>
Top rated system: 5A	1044.60
Lowest rated system: 3B	841.70
Range between top-lowest	202.90
Mean for open-loop systems	940.36
Mean for closed-loop systems	973.32
Top rated open-loop system: 5B	1033.63
Top rated closed-loop system: 5A	1044.60

**Table 32. Overall summary table for rankings of rear-lighting concepts.**

<b>Final Rankings</b>	<b>Using Mean Rating</b>	<b>Using Median Rating</b>	<b>Using Median, Zeros Included</b>	<b>System, Rank Values</b>	<b>Sum of Rank Values</b>	<b>Final System Ranking</b>	<b>Percent Agreeing Meets MUST</b>
1	5A	2	5A	5A, 1/2/1	4	5A	100%
2	5B	5A	5B	5B, 2/3/2	7	5B	100%
3	1	5B	2	2, 5/1/3	9	2	87.5%
4	3A	1	1	1, 3/4/4	11	1	87.5%
5	2	3A	4A	3A, 4/5/7	16	3A	75%
6	4A	4A	4B	4A, 6/6/5	17	4A	87.5%
7	3B	4B	3A	4B, 8/7/6	21	4B	87.5%
8	4B	3B	3B	3B, 7/8/8	23	3B	75%

### Discussion of Results

As can be seen from Table 32, Concepts 5A, 5B, 1, and 2 were generally ranked very high. In addition, Concepts 5A and 5B (the horizontal light bar systems) were the only ones for which all eight experts agreed that the concept met the MUST criterion. A further note of explanation is now in order for Concept 2, the Closed-loop, Radar Activated Auditory and Visual Display in Following Vehicle. From the beginning of Questionnaire 3 development, the VTTI researchers realized that this concept did not strictly meet the objectives of this project, that is, it was not truly a rear-lighting concept. However, it was felt to be important to include this concept in the list because it represents an alternative major logical method of presenting the following driver with the relevant information. Some of the experts expressed concern that if this concept were chosen for further evaluation, it would merely duplicate work already being performed under other initiatives. Seeing how this concept ranked as compared to the rear-lighting concepts provided useful information to the VTTI research staff as well as others working on similar concepts. System 2 was indeed ranked fairly high by the experts, yet it will not be considered for further evaluation in order to avoid duplication of efforts. However, those researchers working on similar systems may be interested in seeing these results. Given that Concept 2 will not be considered for further testing, Concepts 5A, 5B, and 1 emerge as the three top-ranked systems. Note that Concepts 5A, 5B, and 1 also appear as the top-ranked systems using the traditional

KTA method. Possibilities for evaluating these systems in the next two phases of this project are presented in a later section of this report.

### Comments Received on Questionnaire 3

The experts were encouraged to comment on the configurations and they provided several insightful comments which are briefly addressed below.

*Drivers other than the following driver will be distracted.* VTTI researchers certainly realized that this would be an issue, and it resulted in the following criterion: “Is not perceived by surrounding (versus following) drivers as uncomfortable or annoying considering the details of activation, particularly in heavy traffic.” This issue was therefore taken into account in the rating process, although it will be addressed again during Tasks 2 and 3 of the research effort.

*Does not consider the stopped vehicle situation.* In developing the concepts, the idea was that the closed-loop systems, by their very design, would not require a separate stopped vehicle signal. That is, if the lead vehicle were stopped and the following vehicle was approaching at too high a closing rate, then the signal would be activated just as it would be if the lead vehicle were moving and the following vehicle was approaching too quickly. For the open-loop system, there is a remote possibility that the vehicle could be stopped without a signal activation. In most cases in which a vehicle would be standing on the pavement, the driver would have a foot on the brake pedal. Thus, the enhanced rear-lighting system would be activated. However, there may be some low-probability situations in which the driver does not have a foot on the brake pedal. To account for this, the logic diagram for open-loop activation has been modified to activate the rear lighting when the vehicle is standing or moving slowly. Thus, braking *or* zero/low velocity will activate the system. This is discussed further in the section on display activation algorithms.

*Inattention is not the most important contributing factor in most rear-end crashes.* The argument used is that the human inability to accurately detect closing rate is the major contributing factor for rear-end crashes. The literature review, however, pointed in another direction; in study after study of rear-end crashes, inattention/distraction has been shown to be the primary contributing factor, while inability to detect closing rate shows up as a much less frequent cause. This was verified by the results of the law enforcement focus groups held as part of the project. While some laboratory studies have shown that humans are not very good at detecting closing rates at larger distances, this factor does not show up in crash databases. The two possible reasons for lack of citations regarding driver inability to assess closing rates are: 1) the databases are not designed to collect such information (nor are crash report forms), or 2) drivers learn to adapt to this shortcoming in order to be able to drive safely. The true answer probably lies with a combination of these reasons. Nevertheless, given the mandate of the project, we feel it is necessary to base the work ahead on the known major contributing factors rather than on speculative factors, based on the following logic:

1. Crashes are rare events.
2. Human perceptual abilities (such as the ability to perceive closing rate) are fairly constant over time.

3. Human mental and visual distraction vary significantly over time.
4. Given (2) above, if failure to detect closing rate was a major factor in rear-end crashes, rear-end crashes would occur more frequently.
5. There are large numbers of rear-end crashes in which there is either no evidence of braking or evidence of very late braking by the following vehicle. These crashes suggest mental and visual preoccupation, rather than alerted inability to estimate closing rate.

In informal interviews, if people are asked to remember near rear-end crashes when they were at fault (i.e., driving what would have been the striking vehicle), they will much more often remember being visually or mentally distracted prior to the near crash. It is possible to misjudge closing rate, but it usually happens when the closing rate is large (i.e., a fast moving vehicle coming up on a stopped or very slowly moving vehicle). In this case, by the time the threshold of closing rate detection has been passed, there may not be enough time to initiate a corrective response. This circumstance happens relatively infrequently, most often on interstate highways (or similar limited access highways) when a vehicle is stopped or slowed unexpectedly with traffic approaching quickly from the rear.

*The ideal system would use a combination of open- and closed-loop criteria.* For the sake of proof of concept and actually getting the systems wired up for testing, closed- and open-loop systems will continue to be considered separately. Once a concept is proven and ready for deployment, the activation criteria could certainly be fine-tuned and/or combined. However, if a closed-loop system can be made to function correctly, there should be no need for open-loop criteria to be met.

*Concept 2 is not a rear-signaling concept.* This argument has been addressed at length previously in this section.



## CANDIDATE CONFIGURATIONS FOR FURTHER TESTING

The expert panel selected Concepts 5A, 5B, and 1 as the best enhanced rear-lighting configurations. Therefore, the lighting optimization process to be carried out in Task 2 should include at least these three configurations. Note that Concept 5B has two modes: the sequential mode for heavy braking, and the continuous mode for light braking and zero/low vehicle velocity. Concept 5B thus encompasses Concept 5A, which only uses the sequential mode. Concept 1 involves only an inner/outer flash mode using strobes. Therefore, there are three eligible modes for testing: the sequential mode of Concepts 5A and 5B, the continuous mode of Concept 5B, and the flash mode of Concept 1. These modes are hereby recommended for optimization in the test plan for Task 2.

In addition, there has been concern expressed that these concepts are too complex, and that although the activation criteria include the stopped vehicle situation, none of these concepts is a dedicated stopped vehicle signal. Therefore, additional, simpler, signals are also under development (possibly to be applied to the stopped vehicle situation) and will be considered under Task 2 along with the concepts recommended above.

### **Display optimization aspects**

As mentioned, the crash databases suggest that the principle contributing factors in rear-end crashes are inattention to the lead vehicle (mental preoccupation) and visual distraction from the forward view (visual preoccupation). The major problem is believed to be looking away (visual preoccupation), which results in not detecting the imminent collision danger. The second most important factor is looking but not perceiving (mental preoccupation). In the second case, it is believed that the inattention is a result of cognitive load, daydreaming, or lack of alertness. The latter two forms of inattention can be grouped under the heading of problems with vigilance. The enhanced lighting system should be designed so that it overcomes these problems of mental and visual preoccupation in the greatest possible number of circumstances.

The optimization tests of Task 2 should be directed toward rapid and reliable detection of the rear lighting by the following driver. In particular, the enhancement should allow detection using peripheral vision and it should obviously allow improved detection for the “looking but not perceiving” situation. In the latter case, the following driver would be using foveal or near-peripheral vision. Thus, tests should be developed for optimization of detection.

One of the most important questions that must be answered is that of visibility in sunlight. Many rear-end crashes occur under ideal daylight conditions having relatively high ambient illumination. The enhanced lighting systems must have sufficient luminance to be seen (detected) under these conditions. On the other hand, excessive luminance can cause annoyance, glare, discomfort, and flash blindness. Therefore, care must be taken to design a system that can be detected in bright sunlight, yet not cause excessive glare or annoyance at night or under other subdued lighting situations. A system that would automatically adjust the luminance of the signal in response to the ambient lighting condition is one possible solution to this problem. Tests to determine the optimal luminance levels for various ambient lighting conditions should be conducted as part of the optimization process.

A further factor to consider is the potential for annoyance on the part of the following driver who has detected the imminent collision danger. Minimizing the false alarm rate is probably the most effective way to reduce opportunities for annoyance. Other methods include using an annoyance rating scale, and attempting to minimize the annoyance potential while at the same time maximizing the detectability and attention-getting properties of the signal.

A related issue is the potential for annoyance of nearby drivers who are driving in adjacent lanes and who would not be involved in a rear-end collision, regardless of the rear-lighting signal. Careful design to create a signal with directional properties more likely to capture the attention of the following driver, while not being overly conspicuous to the adjacent drivers, could minimize this problem.

Not all configurations will make it beyond the Task 2 optimization phase in which these fundamental questions have been answered: Can the signal be seen under various ambient lighting situations? Can the signal be seen using peripheral vision when looking at something inside the car? Does the signal capture the following driver's attention? Is the signal too annoying to the following or adjacent drivers? One possibility is that the results of the optimization will show that each configuration has desirable traits, and thus the best features of each should be combined for optimum effectiveness. For example, the horizontal light bar with sequential lighting might be found to be an effective signal for alerting the following driver that a crash is imminent, but it might not be capable of attracting the following driver's attention. The strobe system may be found to be effective at capturing attention, but may also be highly annoying to the following driver. A hybrid design could be developed which would consist of a horizontal light bar with a strobe at each end. The strobe would flash only briefly to capture the following driver's attention, then the sequential light bar would be used to convey the warning with less annoyance. The systems chosen for testing under Task 3 might include one or more of these hybrid systems.

## ALGORITHMS FOR ACTIVATION AND DEACTIVATION OF REAR-SIGNALING CONCEPTS

### Closed-loop Algorithm

An algorithm for the required minimum separation to avoid a collision has been developed at VTTI and would be programmed into the radar-based system as described in the next section. The mathematical derivation of this algorithm can be found in Appendix A. When the separation approaches this minimum, the rear-lighting system would be activated. The algorithm is robust over varying speeds of the lead and following vehicles, works for the lead vehicle stopped situation, and includes an allowance for driver perception-reaction time and the coefficient of friction of the tires. When the criteria for imminent rear-end collision are no longer met, the system would deactivate. Thus, potential annoyance (and false triggering) would be minimized. It would be expected that the system would not trigger for traffic stopped at a traffic signal or stop sign (the cases most likely to create annoyance and glare), unless a vehicle approaches from the rear and is in danger of colliding with the stopped vehicle. The logic diagram for activation and deactivation of closed-loop systems has been developed and will be presented later in this section. The relevant detection equation is presented directly below.<sup>2</sup>

The minimum range at which the driver must be alerted is:

$$\text{Eq. 1) } R_{\min} = -v_r t_{pr} + \frac{v_r^2}{2gc_f}$$

where:

$R_{\min}$  is the threshold in ft

$R$  is the present range in ft, taken from the radar

If  $R - R_{\min} > 0$ , no alarm

If  $R - R_{\min} \leq 0$ , alarm

$v_r$  is the range rate between vehicles in ft/sec (negative for following vehicle closing on lead vehicle)

$t_{pr}$  is the driver perception-reaction time in sec

$g$  is the acceleration of gravity (32.2 ft/sec<sup>2</sup>)

$c_f$  is the coefficient of friction of the tires (dimensionless)

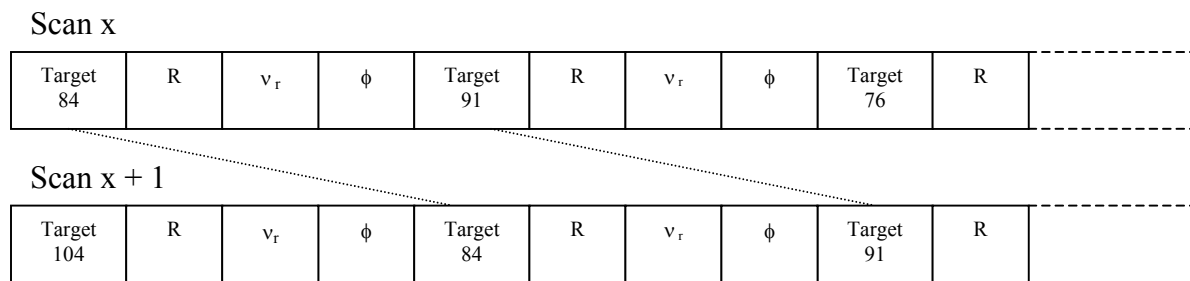
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<sup>2</sup> Equation 1 as shown here is derived for constant or zero lead vehicle velocity. Additional derivations allowing for lead vehicle acceleration and deceleration are currently under development for use in Tasks 2 and 3.

### Closed-loop Rear-lighting Activation Program

This program is intended to activate the rear-lighting system when a rear-end collision is imminent. Criteria to be met include range,  $R$ , equal to or less than  $R_{min}$ , and return angle within a feasible range, that is, between  $\phi_1$  and  $\phi_2$ .

To understand how this program can be developed, it is first necessary to understand how a typical radar unit mounted at the rear of the lead vehicle transfers data. Figure 9 shows a typical data format. As the radar scans and detects a target, it provides a target designation number, range, range-rate, and angle to the target in a serial datastream. If there is more than one target, the datastream continues until all of the target ranges, range-rates, and angles are specified, as shown in Figure 9.



**Figure 9. Depiction of the datastream from the radar antenna unit (note that the stream length varies with the number of targets detected).**

Radar processing is usually consistent in terms of target number designation, but not always. In other words, when it designates the given target by a number, it is usually consistent in this designation in the following scans. However, occasional misdesignations do occur. Also, the datastream may place the targets in any order. These aspects are important for the program design.

Figure 10 shows the main blocks of the activation program. The program is intended to provide rapid response in activating the rear lighting while minimizing false triggering. The program begins by examining two consecutive scans (datastreams) from the radar. Only when data in the two scans are consistent in all indications that a rear-end collision is imminent is the rear lighting activated. Once activated, the rear lighting remains activated for  $t_1$  seconds, which is estimated to be about 2 seconds. If later scans continue to indicate that a collision is imminent, the  $t_1$  second timeout is renewed. Thus, under ordinary circumstances, the rear lighting would be continuously renewed, without extinguishing, as long as the collision danger persists.

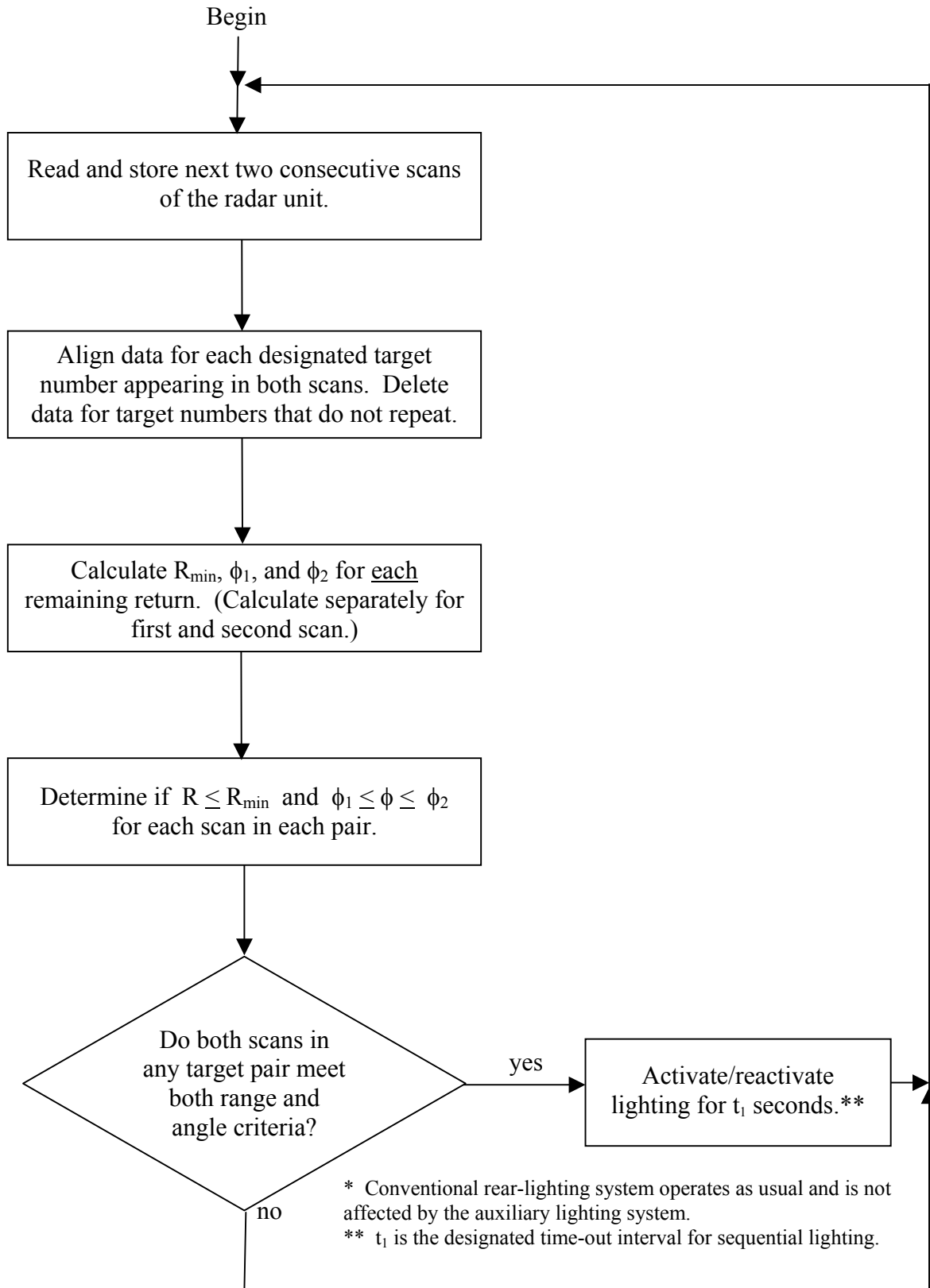


Figure 10. Overall flow diagram for activation of closed-loop rear-lighting system.\*

As the program indicates, the two scans are read and stored. Any targets that do not appear in both scans are deleted. For those remaining, the first scan and the second scan are analyzed separately. If any given target consistently indicates both in the first scan and in the second scan that a collision is imminent (meaning  $R \leq R_{\min}$  and  $\phi_1 \leq \phi \leq \phi_2$ ), then the rear lighting is activated or reactivated for  $t_1$  seconds. If there is no such consistency among the targets, no action is taken. Subsequently, the program repeats using the next two available scans.

Generally, the time required to complete one pass through the program is expected to be relatively short, about 100ms. This would include the time for the radar to produce the two scans and for the processing system to arrive at a decision regarding whether or not to activate/reactivate the rear lighting. To account for this time in the computations, that is, to offset the computation lag, it is only necessary to increase the perception-reaction time value,  $t_{pr}$ , in the equation for  $R_{\min}$  by the amount of the expected lag. Thus, if  $t_{pr}$  is specified as 1.5 seconds, setting it at 1.6 seconds would account for the radar detection and processing time, assuming it is 100ms (or 0.1 sec).

This proposed program seems to offer the right blend of rapid response and immunity from false triggering. Some adjustments may be necessary once the initial program is developed; however, the general concept is expected to be retained.

### **Open-loop Algorithm**

The threshold for the applied pedal force or brake-line pressure required to trigger the sequential display would be developed and programmed into the system. It would be based on moderately rapid deceleration at a specific test speed. Whenever the force/pressure reaches threshold, the rear-lighting system would begin flashing. This force or pressure activation method has advantages. First, it would signal the following driver of moderate or high deceleration of the lead vehicle. Second, if the driver of the *lead* vehicle perceives a following vehicle approaching rapidly, the system could be activated with a moderately strong pulse of brake application even though the lead vehicle is moving slowly or standing still. Thus, the driver of the lead vehicle is given some control over the situation.<sup>3</sup> The display would be lit continuously whenever the driver applies the brakes (the same criterion as is currently used to activate the CHMSL), but the brake pressure criterion would override the brake application criterion. In other words, if the driver's foot is on the brake pedal in a normal manner, the display would be lit continuously. If the driver then applies heavy brake pressure that exceeds the threshold for the applied pedal force or brake-line pressure, the display would begin flashing and would remain flashing until the deactivation criteria are met.

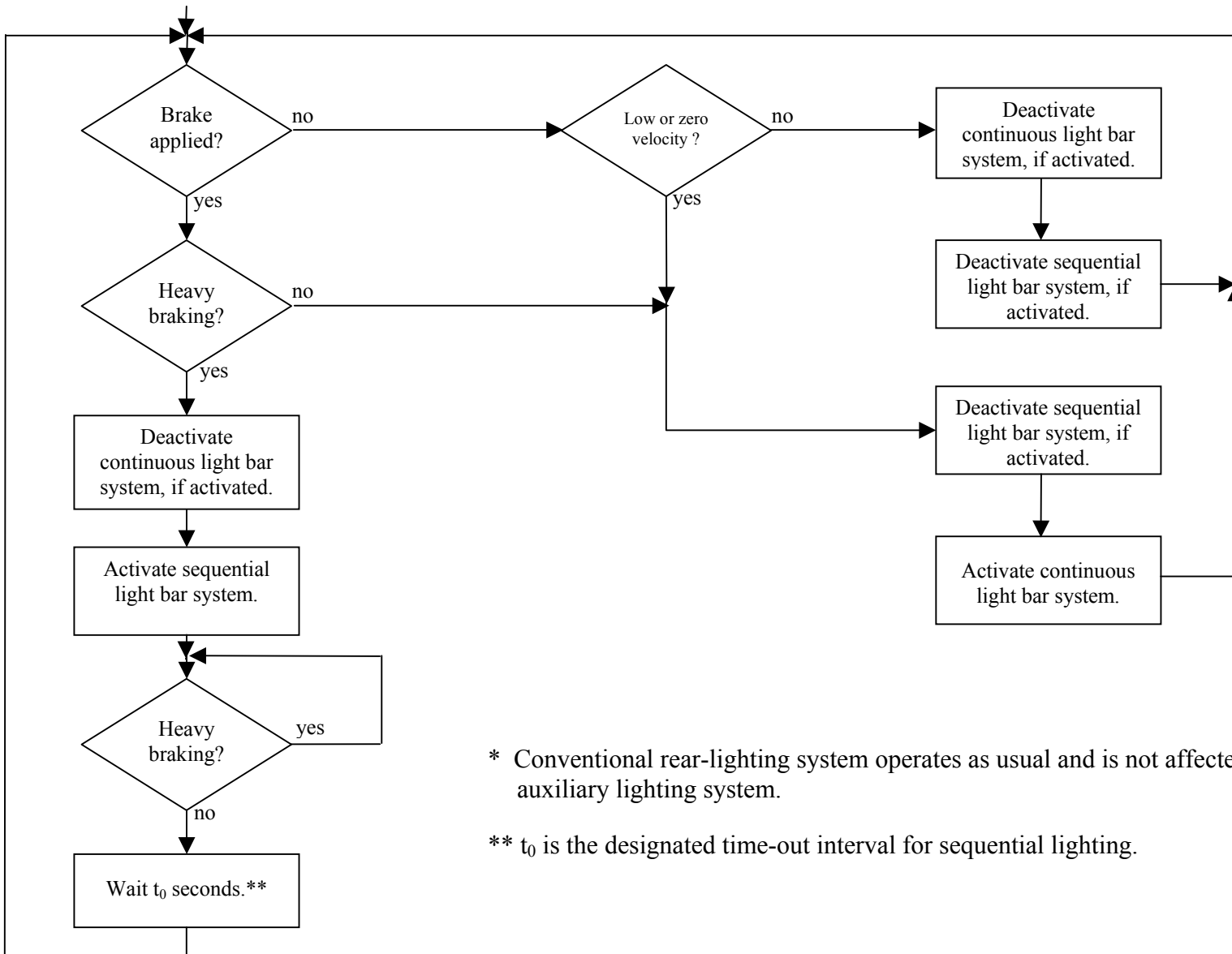
Once the brake force/line pressure activation criterion is no longer met (i.e., the value falls below the set point), the rear-end signal would *not* stop flashing immediately. Instead, the flashing would remain activated for a specified additional time period. This time is estimated to be 4 seconds, but would be determined by experimentation. In other words, the flashing display would be "timed-out" after brake force/line pressure falls below threshold. This timing-out feature is intended to cover likely rear-end crash scenarios in which the following vehicle approaches the lead vehicle shortly after the heavy brake application. During this time interval, the lead vehicle may still be stopped or moving slowly. The time length for timing-out

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<sup>3</sup> It has been pointed out that such a system is subject to abuse by the lead vehicle driver. It is possible to "lock-out" the flashing mode when the lead vehicle is standing or moving slowly. Whether lock-out provides greater benefits would have to be determined by future research.

represents a tradeoff between alerting the following driver and annoyance/false alarm aspects. For normal brake application, the continuous display would be extinguished either by lifting the foot from the brake pedal or by an override to the flashing mode resulting from heavy brake application.

For the open-loop system, there is a remote possibility that the vehicle could be stopped without a signal activation. In most cases where a vehicle would be standing on the pavement, the driver would have a foot on the brake pedal. Thus, the enhanced rear-lighting system would be activated. However, there may be some low-probability situations in which vehicle is stopped but the driver does not have a foot on the brake pedal. To account for this, the logic diagram for open-loop activation, as presented to the expert panel, has been modified to activate the rear lighting when the vehicle is standing or moving slowly. Thus, braking *or* zero/low velocity will activate the system, as shown in Figure 11.



\* Conventional rear-lighting system operates as usual and is not affected by the auxiliary lighting system.

\*\*  $t_0$  is the designated time-out interval for sequential lighting.

**Figure 11. Refined logic flow diagram for open-loop auxiliary rear-lighting system.\***



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**APPENDIX A: DERIVATION OF MINIMUM STOPPING DISTANCE EQUATIONS  
TAKING PERCEPTION-REACTION TIME AND BRAKING INTO ACCOUNT  
(Applicable to Lead Vehicle Moving and Lead Vehicle Stopped)<sup>4</sup>**

**Assumptions:**

Lead vehicle is moving forward at a constant velocity of  $v_{i_l}$  (ft/sec).

Following vehicle is moving forward at a higher initial velocity of  $v_{i_f}$  (ft/sec).

Following vehicle decelerates at  $a$  (ft/sec<sup>2</sup>) when the brakes are applied. (Note that  $a$  is negative for deceleration.)

$t_{pr}$  = perception-reaction time (sec).

$d_{p_f}$  = distance traveled during perception-reaction time by the following vehicle (ft). (Measured at the front bumper.)

$d_{p_l}$  = distance traveled during perception-reaction time by the lead vehicle (ft). (Measured at the rear bumper.)

$c_f$  = tire coefficient of friction (dimensionless).

$d_{b_f}$  = distance traveled by the following vehicle during braking to the lead vehicle's velocity (ft). (Measured at the front bumper.)

$d_{b_l}$  = distance traveled by the lead vehicle during following vehicle's braking (ft). (Measured at the rear bumper.)

$v_{i_f}$  = velocity of the following vehicle during perception reaction time (assumed constant). Also, the initial velocity of the following vehicle at the start of braking (ft/sec).

$v_{i_l}$  = initial constant velocity of the lead vehicle (ft/sec).

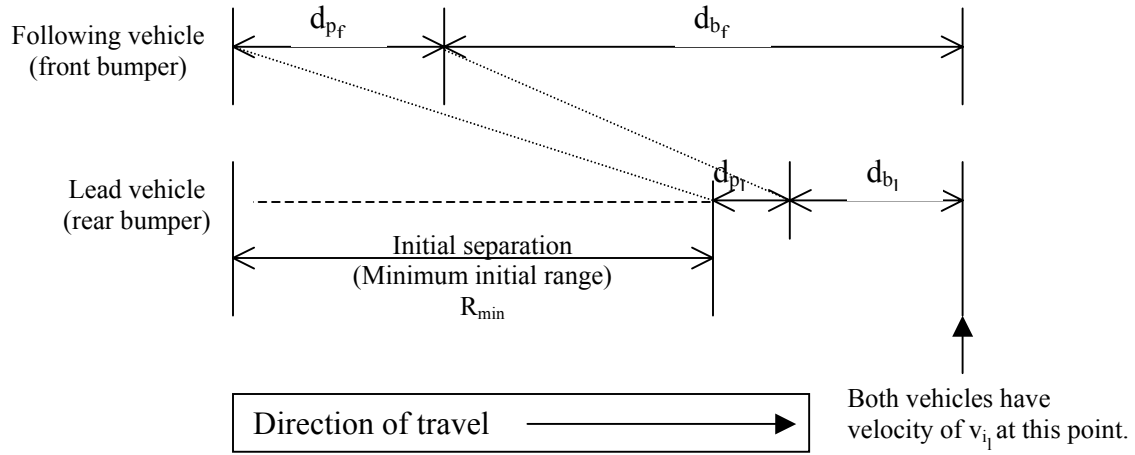
$t_b$  = braking time of the following vehicle (sec).

$g$  = acceleration due to gravity = 32.2 ft/sec<sup>2</sup>.

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<sup>4</sup> The derivations shown here are for constant or zero lead vehicle velocity. Additional derivations allowing for lead vehicle acceleration and deceleration have been developed for use in Tasks 2 and 3.

**Main derivation:**



Required separation at onset of signal:

$$R_{min} = d_{pf} + d_{bf} - d_{pl} - d_{bl}$$

Reduction in closing distance (range) during perception-reaction time:

$$d_{pf} = v_{if} t_{pr}$$

$$d_{pl} = v_{il} t_{pr}$$

$$d_{pf} - d_{pl} = (v_{if} - v_{il}) t_{pr}$$

Braking distance required for following vehicle to slow to lead vehicle's velocity:

$$v_{i_l}^2 = v_{i_f}^2 + 2a d_{b_f}$$

$$d_{b_f} = \frac{v_{i_l}^2 - v_{i_f}^2}{2a}$$

$$a = -g c_f$$

$$d_{b_f} = \frac{v_{i_l}^2 - v_{i_f}^2}{2g c_f}$$

Braking time required for following vehicle to slow to lead vehicle's velocity:

$$v_{i_1} = v_{i_f} + a t_b = v_{i_f} - g c_f t_b$$

$$v_{i_1} - v_{i_f} = -g c_f t_b$$

$$t_b = \frac{v_{i_f} - v_{i_1}}{g c_f}$$

Distance traveled by lead vehicle during following vehicle braking:

$$d_{b_1} = v_{i_1} t_b = v_{i_1} \frac{v_{i_f} - v_{i_1}}{g c_f}$$

Reduction in closing distance (range) during braking:

$$d_{b_f} - d_{b_1} = \frac{(v_{i_f} - v_{i_1})^2}{2g c_f}$$

Required minimum separation to avoid a collision:

$$R_{\min} = d_{p_f} - d_{p_1} + d_{b_f} - d_{b_1}$$

$$R_{\min} = (v_{i_f} - v_{i_1}) t_{pr} + \frac{(v_{i_f} - v_{i_1})^2}{2g c_f}$$

Check of  $d_{b_f} - d_{b_1}$  equation:

$$\text{Assume } v_{i_f} = 88 \text{ ft/sec (60 mph)}$$

$$v_{i_1} = 29.33 \text{ ft/sec (20 mph)}$$

$$c_f = 0.6$$

The time for the following vehicle to reach the lead vehicle velocity is:

$$29.33 = 88 - g c_f, \text{ where } g c_f = (32.2)(0.6)$$

Therefore,

$$t = \frac{88 - 29.33}{(32.2)(0.6)} = 3.03675 \text{ sec}$$

In this time, the lead vehicle has traveled:

$$(29.33)(3.03675) = 89.067 \text{ ft}$$

The distance traveled by the following vehicle in braking is:

$$29.33^2 = 88^2 - 2gc_f d, \text{ where } gc_f = (32.2)(0.6)$$

$$2gc_f d = 88^2 - 29.33^2$$

$$d_{br} = \frac{88^2 - 29.33^2}{2(32.2)(0.6)} = \frac{7744 - 860.2489}{38.64} = 178.151 \text{ ft}$$

Subtracting the distance of the lead vehicle gives the minimum separation:

$$178.151 - 89.067 = 89.084 \text{ ft}$$

Now, by the equation:

$$\frac{(v_{i_f} - v_{i_l})^2}{2gc_f} = \frac{(88 - 29.33)^2}{2(32.2)(0.6)} = 89.0030 \text{ ft}, \text{ which serves as a check.}$$

Examples:

$$\begin{aligned} \text{Parameters: } t_{pr} &= 1.2 \text{ sec} \\ c_f &= 0.6 \end{aligned}$$

1. Assume lead vehicle stopped ( $v_{i_l} = 0$ ) and following vehicle at 88 ft/sec (60 mph)

$$R_{\min} = (88 - 0)(1.2) + \frac{(88 - 0)^2}{2(32.2)(0.6)} = 105.6 + 200.4 = 306 \text{ ft}$$

2. Assume lead vehicle at 6 mph ( $v_{i_l} = 8.8$  ft/sec) and following vehicle at 88 ft/sec (60 mph)

$$R_{\min} = (88 - 8.8)(1.2) + \frac{(88 - 8.8)^2}{2(32.2)(0.6)} = 95.04 + 162.34 = 257.38 \text{ ft}$$



3. Assume lead vehicle at 55 mph (to check calculations) ( $v_i = 80.667$  ft/sec) and following vehicle at 60 mph (88 ft/sec)

$$R_{\min} = (88 - 80.667)(1.2) + \frac{(88 - 80.667)^2}{2(32.2)(0.6)} = 8.7996 + 1.3916 = 10.19 \text{ ft}$$

**Equation transformed for radar at rear of lead vehicle:**

Equation must be written in terms of lead vehicle's velocity,  $v_i$ , and range rate between vehicles.

Let  $v_r$  = range rate between vehicles in ft/sec

$$v_r = v_i - v_{i_f} \quad \text{Note that } v_r \text{ is negative for closing following vehicle.}$$

Then:

$$v_{i_f} = v_i - v_r$$

$$R_{\min} = (v_i - v_r - v_{i_f}) t_{pr} + \frac{(v_i - v_r - v_{i_f})^2}{2gc_f}$$

$$R_{\min} = -v_r t_{pr} + \frac{v_r^2}{2gc_f}$$

Where  $v_r$  is negative for closing rear vehicle. Note that  $v_i$  drops out.

Example:

$$\text{Parameters: } t_{pr} = 1.2 \text{ sec}$$

$$c_f = 0.6$$

Assume lead vehicle at 6 mph ( $v_i = 8.8$  ft/sec) and following vehicle at 60 mph (88 ft/sec)

$$v_r = 8.8 - 88 = -79.2 \text{ ft/sec}$$

$$R_{\min} = -(-79.2)(1.2) + \frac{(-79.2)^2}{2(32.2)(0.6)} = 95.04 + 162.335 = 257.375 \text{ ft}$$

This checks with the earlier result.

**Equation transformed for radar at front of following vehicle:**

Equation must be written in terms of following vehicle's velocity,  $v_{i_f}$ , and range rate between vehicles.

$$v_r = v_{i_1} - v_{i_f} \quad \text{Note that } v_r \text{ is negative for closing following vehicle.}$$

Then:

$$v_{i_1} = v_r + v_{i_f}$$

$$R_{\min} = (v_{i_f} - v_r - v_{i_f}) t_{pr} + \frac{(v_{i_f} - v_r - v_{i_f})^2}{2gc_f}$$

$$\boxed{R_{\min} = -v_r t_{pr} + \frac{v_r^2}{2gc_f}}$$

Note that this equation is identical to the earlier equation; therefore, use for either application.

## SUMMARY

The minimum range at which the driver must be alerted is:

$$R_{\min} = -v_r t_{pr} + \frac{v_r^2}{2gc_f}$$

where:

$R_{\min}$  is the threshold in ft

$R$  is the present range in ft, taken from the radar

If  $R - R_{\min} > 0$ , no alarm

If  $R - R_{\min} \leq 0$ , alarm

$v_r$  is the range rate between vehicles in ft/sec (negative for following vehicle closing on lead vehicle)

$t_{pr}$  is the driver perception-reaction time in sec

$g$  is the acceleration of gravity (32.2 ft/sec<sup>2</sup>)

$c_f$  is the coefficient of friction of the tires (dimensionless)

Example:

Lead vehicle traveling at 15 mph, ( $v_{i_l} = 22$  ft/sec)

Following vehicle traveling at 55 mph, ( $v_{i_f} = 80.67$  ft/sec)

Perception-reaction time is 1.2 sec, ( $t_{pr} = 1.2$  sec)

Coefficient of friction is 0.6, ( $c_f = 0.6$ )

$$v_r = 22 - 80.67 = -58.67 \text{ ft/sec}$$

$$R_{\min} = (58.67)(1.2) + \frac{58.67^2}{2(32.2)(0.6)} = 70.40 + 8908 = 159.48 \text{ ft}$$

Alarm activated when range  $R \leq 159.48$  ft

Important note:

The equation for  $R_{\min}$  is not dependent on the absolute velocity of either vehicle.

$R_{\min}$  is only dependent on the relative velocity of closure of the two vehicles, that is, closing rate.

Thus,  $R_{\min}$  is the same for the following cases:

Lead vehicle at 20 mph, following vehicle at 60 mph

Lead vehicle at 10 mph, following vehicle at 50 mph

Lead vehicle at 0 mph, following vehicle at 40 mph

Calculations for graphing. Assume  $t_{pr} = 1.2$ ,  $c_f = 0.6$

Calculate for closing speeds of  $-10$ ,  $-20$ ,  $-30$ ,  $-40$ ,  $-50$ ,  $-60$ , and  $-70$  mph

Corresponding to  $-14.67$ ,  $-29.33$ ,  $-44$ ,  $-58.67$ ,  $-73.33$ ,  $-88$ , and  $-102.67$  ft/sec

$$R_{\min 10} = (14.67)(1.2) + \frac{14.67^2}{2(32.2)(0.6)} = 17.604 + 5.570 = 23.17 \text{ ft}$$

$$R_{\min 20} = (29.33)(1.2) + \frac{29.33^2}{38.64} = 35.196 + 22.263 = 57.46 \text{ ft}$$

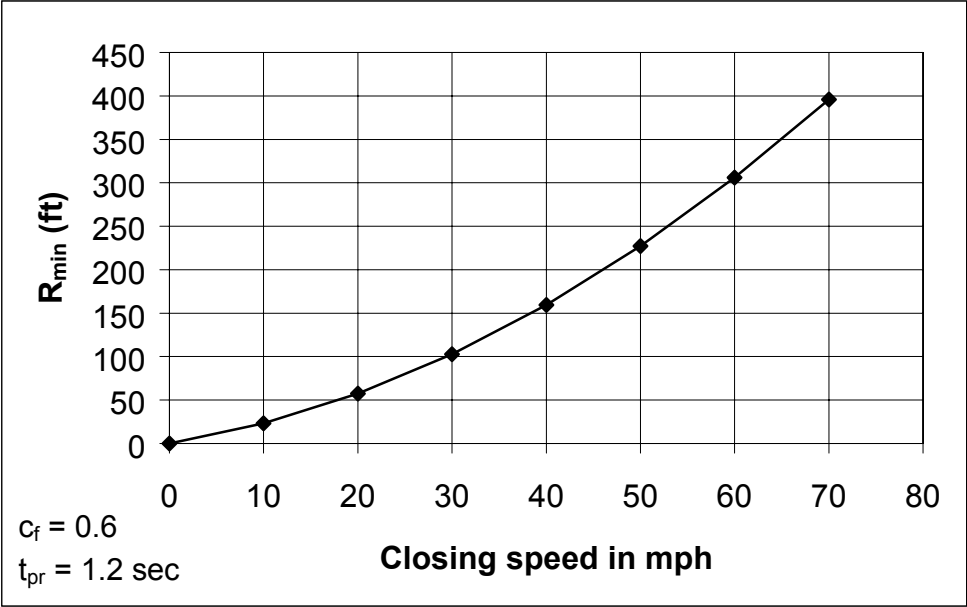
$$R_{\min 30} = (44)(1.2) + \frac{44^2}{38.64} = 52.8 + 50.104 = 102.9 \text{ ft}$$

$$R_{\min 40} = (58.67)(1.2) + \frac{58.67^2}{38.64} = 70.404 + 89.083 = 159.49 \text{ ft}$$

$$R_{\min 50} = (73.33)(1.2) + \frac{73.33^2}{38.64} = 87.996 + 139.164 = 227.16 \text{ ft}$$

$$R_{\min 60} = (88)(1.2) + \frac{88^2}{38.64} = 105.6 + 200.414 = 306.01 \text{ ft}$$

$$R_{\min 70} = (102.67)(1.2) + \frac{102.67^2}{38.64} = 123.204 + 272.804 = 396.00 \text{ ft}$$



DOT HS 809 425  
March 2002



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