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Evaluation of Enhanced Brake Lights Using Surrogate Safety Metrics

Task 2 & 3 Report

Development of a Rear Signaling Model and
Work Plan for Large Scale Field Evaluation

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David Band was the Task Order Manager (TOM) for this project

16. Abstract

This report documents efforts undertaken as part of a larger program of research involving a series of inter-related studies and research projects intended to reduce the frequency and severity of rear-end crashes via enhancements to rear-brake lighting. It outlines current efforts leading to the development of a rear signaling model to estimate the relative safety benefits of various enhanced braking signal approaches on the incidence of rear-end crashes, as well as the development of a detailed work plan for conducting a Field Operational Test of candidate rear signaling systems. This preliminary model is a first effort designed to see if enhanced rear signaling systems can provide safety benefits. This model is not comprehensive, nor does it model any of the system costs. The results from this preliminary model found that use of brake signal configurations which simultaneously flash the brake lamps (both outboard and CHMSL units) at 5 Hz were found to be effective, reducing the crash rate by as much as a 5.1% (95% confidence interval: 3.5%-6.7%), equivalent to 21,723 fewer annual rear-end crashes. The model also found that effectiveness of the simultaneous flashing signal was moderated by both 1) signal luminance (and brightness) and 2) activation, or triggering criteria. Additional efforts are needed to increase model reliability by gathering additional data to populate model parameters, and to validate model outputs to ensure predictions are generally reflective of real-world performance. A research work plan is also presented for implementing a large-scale Field Operational Test intended to evaluate the real-world effectiveness of one or more rear signaling system implementations.

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EXECUTIVE SUMMARY

This report documents efforts undertaken as part of a larger program of research involving a series of inter-related studies and research projects, sponsored by the National Highway Traffic Safety Administration and conducted by Virginia Tech's Transportation Institute, intended to reduce the frequency and severity of rear-end crashes. It outlines current efforts (third in the series) leading to the development of a rear signaling model to estimate the relative safety benefits of various enhanced braking signal approaches on the incidence of rear-end crashes, as well as the development of a detailed work plan for conducting a Field Operational Test of candidate rear signaling systems. This work was performed under a Task Order whose primary goal was to aid in the development and research needed to support the evaluation of promising rear signal systems, including the development of a surrogate safety metric for evaluating the effectiveness of rear brake signal approaches.

Rear-end crashes account for more than 29 percent of all U.S. vehicle crashes, contributing to approximately 5.4 percent of traffic deaths in the United States (National Transportation Safety Board, NTSB, 2001). Research undertaken as part of this program suggests that failure to respond (or delays in responding) to a stopped or decelerating lead vehicle is generally a result of distraction, and in particular, improper allocation of visual attention (Lee, Llaneras, Klauer, and Sudweeks, 2007). Thus, VTTI's approach to the rear-end crash problem has argued that a successful rear signaling system would work to redirect driver visual attention to the forward roadway (for cases involving a distracted driver), as well as improve the driver's ability to discern hard braking events by increasing the saliency or meaningfulness of the brake signal (for attentive drivers). Given this framework, eye-drawing capability is believed to represent the most effective means of redirecting a distracted driver's attention to the forward view when a rear-end crash is imminent.

The primary goal of the current project was to aid in the development and research needed to support the evaluation of promising rear signal systems, including the development of a non-crash, safety-related metric of enhanced brake light systems – a surrogate safety metric for evaluating the effectiveness of rear brake signal approaches. Development of surrogate safety measures and metrics represents an important step towards supporting system evaluations such as a large scale Field Operation Test (FOT) of candidate rear signaling system(s). Two primary research tasks were undertaken to support the evaluation of promising rear signal systems: 1) Development of a rear signaling model to estimate the relative safety benefits of various enhanced braking signal approaches on the incidence of rear-end crashes, and 2) Formulation of a detailed Work Plan for a large-scale rear signaling Field Operational Test (FOT).

A computer-based simulation model for estimating effectiveness of enhanced brake light signaling systems was developed and implemented using Matlab's Simulink programming language. The model included key factors believed to underlie and contribute to rear-end crashes, driver performance and behavior dimensions, as well as characteristics of the rear signaling systems themselves. The model is expected to aid in the identification and selection of promising rear brake signal approaches by estimating signal effectiveness in terms of eliminating and/or reducing the incidence of rear-end crashes. Model components allow rear-end crash scenarios and signal system properties to be defined, and weighs driver-system performance in a series of Monte-Carlo simulation runs to model performance under a wide range of rear-end crash scenario conditions. The model serves as a useful decision-making tool allowing the relative safety benefit of alternative enhanced rear brake signal approaches to be compared, and identifying the mechanisms underlying predicted performance gains in order to guide system design changes.

The model structure itself also serves as a convenient framework for organizing and structuring available data allowing research and data needs to be identified and defined, and was designed to be flexible and expandable allowing new information and additional factors to be integrated and modeled as data becomes available. The model was exercised to assess the effectiveness of alternative signaling approaches using available data from published studies and reports, statistics on the crash problem from GES and associated database analyses, naturalistic studies or Field Operational Tests, as well as targeted rear lighting studies conducted under this research program.

Model results found that of the brake signal configurations tested, those which simultaneously flash the brake lamps (both outboard and CHMSL units) at 5 Hz were found to be effective, reducing the crash rate by as much as a 5.1% (95% confidence interval: 3.5%-6.7%), equivalent to 21,723 fewer annual rear-end crashes; these signals were also found to impact crash severity levels. The model also found that effectiveness of the simultaneous flashing signal was moderated by both 1) signal luminance, or brightness and 2) activation, or triggering criteria.

Estimates generated by the model under this current project should be interpreted as preliminary high-level order-of-magnitude estimates, restricted by the available data and underlying simplifying assumptions. Additional efforts are needed to increase model reliability by gathering additional data to populate model parameters, and to validate model outputs to ensure predictions are generally reflective of real-world performance. For example, the model does not currently take into account the impacts or costs associated with false or nuisance system activations which may erode driver trust and responsiveness to these signals, as well as increase driver annoyance. Since the model framework is flexible, it can be expanded and updated as new data elements are gathered leading to more robust and reliable effectiveness estimates.

A research work plan is also presented for implementing a large-scale Field Operational Test intended to evaluate the effectiveness of one or more rear signaling system implementations.

Numerous issues are presented and discussed, including the philosophy of the FOT test fleet, the FOT location, continuous vs. triggered data collection, and use of safety surrogate measures to index system effectiveness. This plan prescribes alternative means to empirically evaluate the estimated crash benefits of enhanced rear brake signal approaches via a Field Operational Test using a light vehicle fleet.

Chapter 1. Introduction & Background

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

Data suggest that eye glance patterns (moderated by distraction), not roadway or traffic factors, are the most significant predictor of whether a near-crash situation evolves into a crash for conflicts with lead and following vehicles (rear-end crashes). Analysis of 100-Car data (Lee, Llaneras, Klauer, and Sudweeks, 2007), for example, found that most drivers are attentive and able to detect and respond to a stopped or decelerating lead vehicle, and that failure to respond (or delays in responding) to a stopped or decelerating lead vehicle is generally a result of distraction, and in particular, improper allocation of visual attention. Thus, VTTI's approach to the rear-end crash problem has argued that a successful rear signaling system would work to redirect driver visual attention to the forward roadway (for cases involving a distracted driver), as well as improve the driver's ability to discern hard braking events by increasing the saliency or meaningfulness of the brake signal (for attentive drivers).

This report documents work undertaken as part of a larger series of inter-related studies and research projects, sponsored by the National Highway Traffic Safety Administration and conducted by Virginia Tech's Transportation Institute, to further evaluate and select optimum candidate signal applications to address rear-end crashes.

Background

VTTI, in conjunction with the National Highway Traffic Safety Administration (NHTSA), embarked on a multi-year effort to design and evaluate various rear signaling systems that would warn drivers of a slowing or stopped lead vehicle. The first rear lighting project identified several novel signals with increased conspicuity which led to improved reaction time and shorter stopping times. A second follow-on project was undertaken to confirm the potential real world benefits of a more attention-getting brake signal; this included an analysis of 100-Car data to examine driver behavior related to rear-end crash and near crash events. The work also included an on-road data collection effort using candidate rear signaling systems intended to assess the feasibility of capturing key performance metrics (e.g., following vehicle driver parameters including braking onset, braking magnitude, and eye-glance locations) and led to the development of preliminary functional system requirements.

Current Project Purpose and Objectives

The primary goal of the current project was to aid in the development and research needed to support the evaluation of promising rear signal systems, including the development of a non-crash, safety-related metric of enhanced brake light systems – a surrogate safety metric for evaluating the effectiveness of rear brake signal approaches. Previous large scale FOTs on rear lighting have involved the instrumentation of large fleets of vehicles and have historically taken long periods of time to acquire crash data (Mortimer, 1981; Voevodsky, 1971). Through novel evaluation techniques involving the use of surrogate measures of rear end crashes (e.g., near crashes, critical incidents, etc.), signaling systems could be tested both faster and more economically. Development of surrogate safety measures and metrics represents an important step towards supporting system evaluations such as a large scale Field Operation Test (FOT) of candidate rear signaling system(s). Three research tasks with subsidiary activities were defined to support this goal:

1. **Characterize and develop rear lighting signals most likely to improve driver reaction to hard braking or post hard-braking, recently-stopped lead vehicles**. This work is intended to refine and specify the properties of rear signaling systems, including: criteria for signal activation and duration; and practical implementation and integration issues for performing a Field Operational Test (FOT) of candidate rear signaling systems. This involved identifying key issues and remaining knowledge gaps identified in the series of NHTSA-sponsored rear lighting research efforts. The work required additional empirical testing to further refine and evaluate signal characteristics; this included identifying and quantifying the expected benefits of signal approaches intended to cue hard deceleration events as well as recently-stopped lead vehicles and their effect on driver reaction times for both alert and distracted drivers. Emphasis was devoted to evaluating signal approaches likely to be adopted by industry.

2. **Develop a rear signaling model to estimate the relative safety benefits of various enhanced braking signal approaches on the incidence of rear-end crashes**. The model identified and related causal factors contributing to rear-end crashes and specified how candidate signal approaches act to intervene or otherwise moderate performance to reduce or mitigate the incidence of rear-end crashes. Associated objectives included: a) Populating model parameters (key factors, causal relationships, countermeasures, disbenefits) with data derived from available sources, as well as analytic and empirical activities to address data and knowledge gaps; b) Developing, implementing, and exercising the model in a suitable computerized format to enable estimated safety benefits for signal concepts to be generated.

3. **Formulate a detailed Work Plan for a large-scale rear signaling Field Operational Test (FOT)**. This task culminated in the development of a detailed work plan for conducting a Field Operational Test of candidate rear signaling systems. Numerous issues are presented and discussed, including the philosophy of the FOT test fleet, the FOT location, continuous vs. triggered data collection, etc. The work plan details the following elements:

    - Baseline data collection approach (research design)
    - Fleet type (type of vehicles and drivers)
    - Location
    - Number of vehicles
    - Length of FOT
    - Participants – number, characteristics, and length of participation
    - Continuous vs. triggered data collection
    - Enhanced lighting type
    - Dependent variables

Work performed in support of the first task included a series of inter-related research studies and supporting activities to further characterize and develop rear brake light signals likely to improve driver reaction to hard braking lead vehicle events, emphasizing unique and novel approaches not previously studied. Full details of this work are documented in the published Task 1 report (Weirwille, Llaneras, and Neurauter, 2009), and are not presented as part of this report. The Task 1 report describes studies undertaken to assess LEDs and to determine which type and configuration provides the greatest advantages for rear-end enhanced rear lighting systems. To summarize, the first study (LED optimization) characterized a sample of existing, commercially available automotive LED brake light arrays and documented the current state-of-the-art for LED technology. This work also developed optimized signal lighting configurations, including specifications for LED signal approaches (flash frequencies, luminance levels, patterns). The second empirical study (static testing) narrowed the pool of available signal approaches using static field evaluations intended to assess subjective impressions of signal attributes (attention getting and glare) as well as eye-drawing capability of candidate signals for drivers who were looking away from the forward view. The third study (public roadway evaluation) captured driver responses to signal activations under naturalistic settings via observational methods using vehicles equipped with candidate signals and on-board instrumentation. This on-road study also addressed unintended consequences associated with the novel experimental signal approaches. Each step along this research path was intended to further refine signal attributes and narrow the set of candidate signals for downstream evaluation. Analytic activity was also undertaken in order to further the development of system specifications, including developing a scientific basis for activation criteria and thresholds and special cases for open loop enhanced rear lighting. Together, this work increased the state-of-knowledge and development of rear-brake signal approaches. Results indicate that newer rear signaling designs can be very effective at drawing drivers' eyes back to the forward roadway, and that flashing and luminance are two important signal properties moderating effectiveness (attention-getting). Significant performance gains can be achieved via use of LED signal approaches which both flash and increase signal intensity or lamp luminance.

This report focuses on the Task 2 & 3 activities leading to the development of a computer-based model to estimate safety benefits of alternative rear signaling approaches and concepts, and the development of a work plan to support a large-scale Field Operational Test of candidate rear signaling systems for light vehicles.

Supporting Sub-Task Activities

Sub-Task 1. Formulate a Benefits Estimation Model Which Specifies Relationships Between Candidate Rear Lighting Signal Characteristics and Rear-End Crash Causal Factors

During this task, VTTI developed a model to estimate the safety benefits of enhanced rear brake signaling approaches. The model included key factors believed to underlie and contribute to rear-end crashes, driver performance and behavior dimensions, as well as characteristics of the rear signaling systems themselves (crash countermeasures). Model components specified relationships among these factors, allowing system effectiveness and impacts of unintended consequences to be considered in estimating crash likelihood and severity for given countermeasures. The model offers the following advantages:

- Allows key parameters and factors to be organized and presented in a meaningful way
- Enables relative effectiveness of different signaling approaches to be estimated
- Takes advantage of existing data sources which can be used to populate the model
- Outlines areas in need of additional research, and undertakes targeted studies to capture data to populate the model

Sub-Task 2. Populate Model Parameters Using Available Data Sources

Once developed, individual parameters of the model were populated with data, allowing computations to be executed and outputs to be generated in the form of crash likelihood and severity estimates. To the extent feasible, model components included some form or level of information (data distributions, variable ranges, etc) derived from existing datasets, available literature, and/or previous rear signaling research efforts. VTTI made use of the available 100-Car Study data, for example, to specify pre-crash kinematic situations describing vehicle following and headways, as well as typical driver brake response times and deceleration levels for different rear-end crash events. Nevertheless, the amount and nature of available data for some factors was limited (e.g., information related to potential system disbenefits).

Sub-Task 3. Identify Knowledge and Research Gaps (Areas or Parameters Where Little or No Data Exist) and Perform Targeted Studies to Populate the Model

This task intended to increase available knowledge by identifying and targeting model areas which have little or no available data, and thus in need of further research and specification. VTTI performed analytic and empirical activities (e.g., analysis of 100-Car data, research studies) in order to yield suitable data for model parameters where limited data currently exist and are needed to drive model estimates. Given the scope and time-frame of this effort, VTTI prioritized the research needs and developed appropriate methods and approaches for gathering additional data. Research needs included: characterizing potential unintended consequences associated with various signaling approaches, and specifying impacts of signal luminance, among other issues.

Sub-Task 4. Implement and Exercise the Model Using a Suitable Computer Software Package

Once the model was developed and specified, VTTI implemented and exercised the model using a computer software package (e.g., Matlab Simulink); the structure and operation of the computerized model allowed the effects of rear signaling countermeasures on rear-end crashes to be estimated. The simulation program also allows the relative effectiveness of various signaling approaches to be assessed. The resulting software package was provided to NHTSA at the conclusion of the project allowing additional estimates and/or model adaptations to be performed in the future.

Thus, work undertaken as part of this effort led to the development of 1) a rear-end crash model used to estimate safety benefits of alternative rear signaling approaches and concepts, and 2) a work plan which prescribes a means to empirically evaluate the estimated crash benefits of enhanced rear brake signal approaches via a Field Operational Test using a light vehicle fleet.

Chapter 2. Development of Rear Signaling Model

The main goal of Task 2 activity is to develop a model to estimate the relative safety benefits of various enhanced signal approaches on the incidence or likelihood of rear-end crashes. The model is expected to aid in the identification and selection of promising rear brake signal approaches by estimating signal effectiveness in terms of eliminating and/or reducing the incidence of rear-end crashes. Four inter-related sub-task activities were detailed as part of the process leading to the development of this effectiveness estimation model, including:

1) Formulating a benefits estimation model which specifies relationships between candidate rear lighting signal characteristics and rear-end crash causal factors,
2) Populating model parameters using available data sources,
3) Identifying knowledge and research gaps and perform targeted studies to populate the model, and
4) Implementing and exercising the model using a suitable computer software package.

Conceptual Model Structure & Function

The conceptual model, illustrated in Figure 1, includes key factors believed to underlie and contribute to rear-end crashes, as well as crash countermeasure characteristics associated with rear signaling systems. As shown in the figure, primary high-level model structures include a Crash Scenario Definition and a System Simulation Model. The former component specifies the crash type, vehicle kinematic conditions, and environmental characteristics that define the operating space of the model. Together, these components define individual rear-end scenarios that are subsequently fed into the System Simulation Model. Signal system characteristics and performance aspects are specified with this component as are driver characteristics to formulate an estimated system performance function. Aspects such as signal conspicuity, triggering criteria, potential disbenefits, and driver attentiveness and cognitive state are defined and considered in calculating the system performance function. This information is combined with weighted exposure data to arrive at an overall effectiveness estimate expressed in terms of crash outcomes and severity.

Individual model components, depicted in Figures 2-4, also specify relationships within these structures, allowing system effectiveness and impacts of unintended consequences to be considered in estimating crash likelihood and severity for given countermeasures.

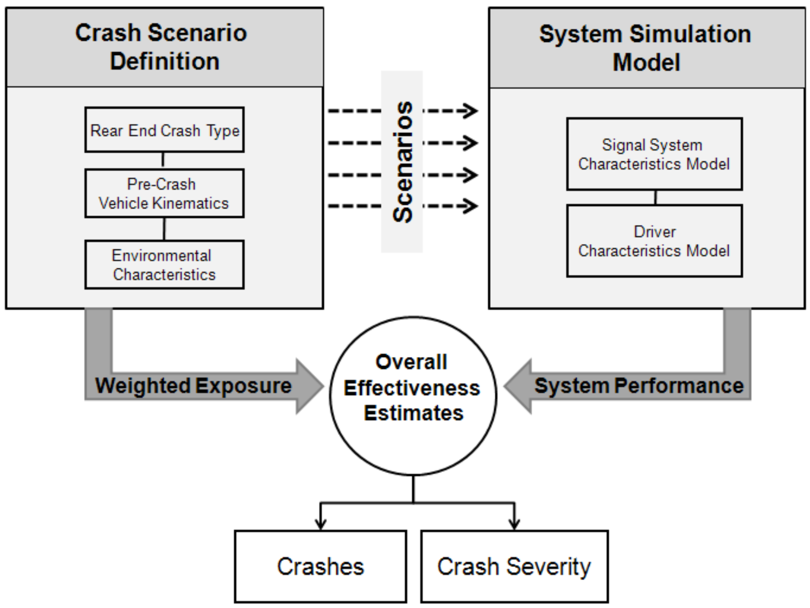

Figure 1. Overall Conceptual Model Components and Flow

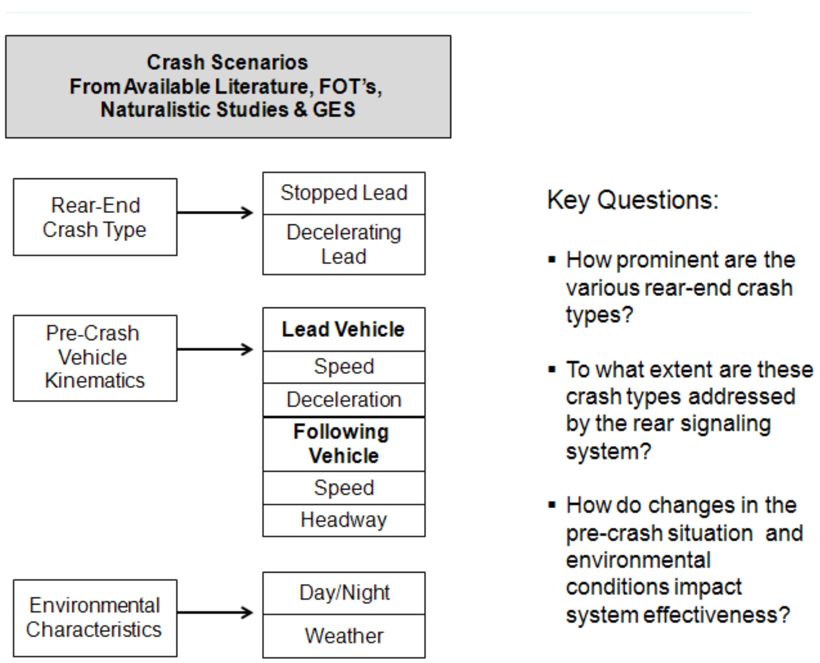

Figure 2. Model Elements Related to Crash Scenario Definition

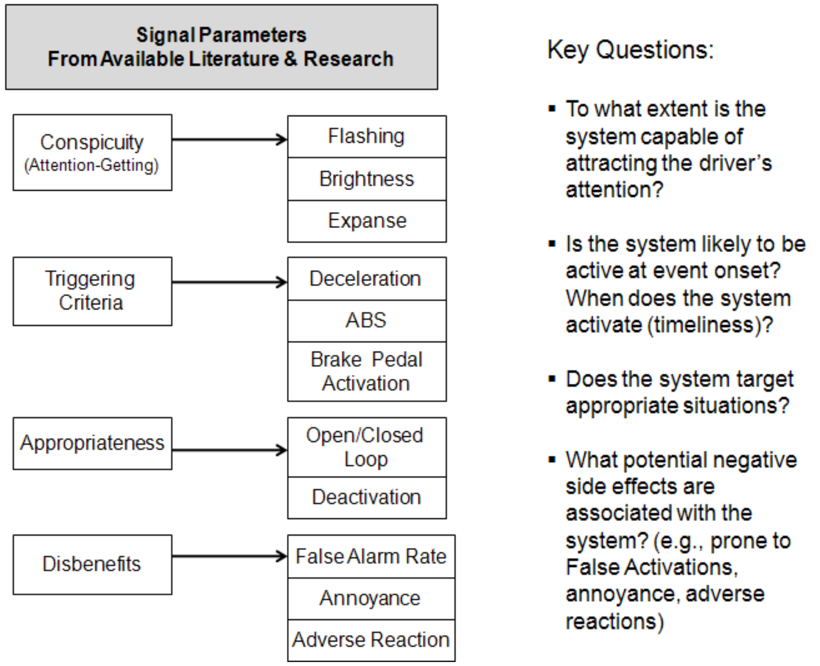

Figure 3. Model Elements Related to Signal Parameters

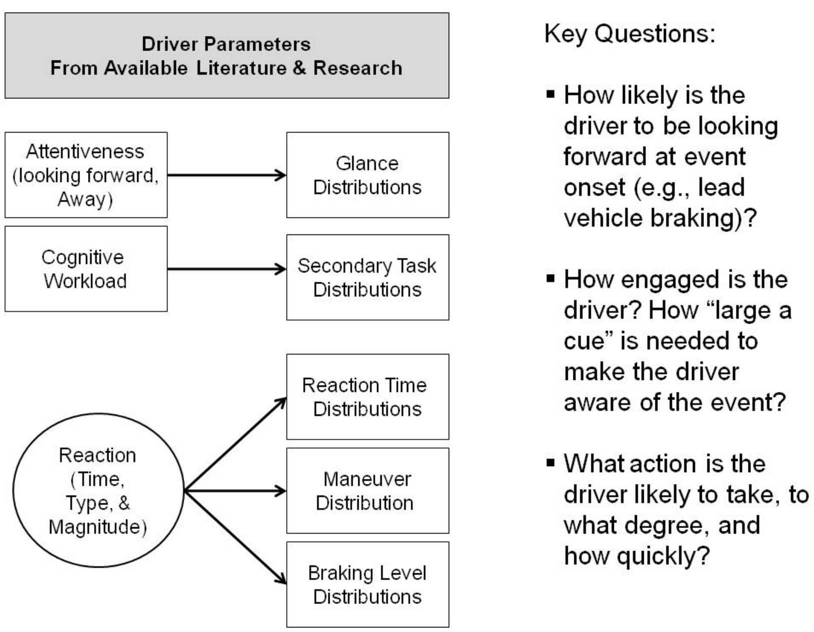

Figure 4. Model Elements Related to Driver Parameters

To summarize, the model for estimating benefits of enhanced brake light signaling systems is comprised of three major components. The first defines crash types and scenarios and takes into account the frequency of occurrence of these scenarios in calculating effectiveness for a set of defined scenarios. The second component considers the characteristics and properties of the enhanced signal system itself and how these factors moderate driver performance under defined scenarios. The third component weighs the driver-system performance in a series of Monte-Carlo simulation runs to model outcomes across a wide spectrum of defined crash scenarios and conditions; these data are subsequently used to generate an overall effectiveness estimate expressed in terms of crash outcomes and severity measures. The model is intended to allow the relative safety benefit of alternative enhanced rear brake signal approaches to be compared, and to serve as a useful decision making tool by identifying the mechanisms underlying predicted performance gains or lack thereof. This information may be used to eliminate or reduce the number of viable candidate rear signaling approaches, and/or to guide system design changes.

Model Development Process

Ideally, all model components would include some form or level of information (data distributions, variable ranges, etc) derived from existing datasets, available literature, previous rear signaling research efforts, and analysis of naturalistic datasets. Although the amount and nature of available data for some factors may currently be limited (e.g., information related to potential system disbenefits), the model framework provides complete flexibility in how individual elements are populated; the model is capable of generating estimates to make use of available data and does not necessarily require all components to be populated with data.

The conceptual model, presented above, was developed into a computer-based simulation model using Matlab's Simulink programming language. In order to implement and run the computer-based model, data for each of the model parameters were defined using a variety of available data sources, including data from available studies and reports, statistics on the crash problem from GES and associated database analyses, naturalistic studies or Field Operational Tests, as well as targeted rear lighting studies conducted under this, or other related, research programs. As part of this process, efforts were undertaken to gather data needed to populate the model, and to identify knowledge gaps where little or no data exist. Thus, the model structure itself served as a convenient framework for organizing and structuring available data allowing research and data needs to be identified and defined. As discussed, the model was designed to be flexible and expandable allowing new information and additional factors to be integrated and modeled as it becomes available. Nevertheless, a working model was developed based on existing data and a set of rear signaling systems.

Current Data Needs & Knowledge Gaps

Table 1 details the model components and availability of data for each element. Many of the data items were obtained or derived through the use of existing datasets, primarily via analysis of the 100-Car Study and GES data. These items include: crash type rates, pre-crash kinematics (lead vehicle speeds and deceleration rates, following distances or headways, and following vehicle speeds), driver reactions (times, types, and magnitudes), driver cognitive workload levels, and driver eye-glance patterns. Note that the availability of these datasets do not necessarily imply that the data elements were in a readily usable form; some additional analysis and or data transformations were needed. Relatively little data, however, are available to characterize signal parameters related to conspicuity, triggering criteria, and system disbenefits. These areas represent potential knowledge gaps and targets for additional research under this sub-task.

The rear signaling benefits estimation model used the data elements specified in the table to generate a number of estimates relating to the:

- System effectiveness
- Potential crash reduction in annual crashes
- System harm reduction
- Potential harm reduction

These measures are the main outputs of the model. Other measures and probabilities can be derived from the data produced by the model that is used to generate these estimates, and used to describe the conditions under which crashes (if present) tend to occur.

Table 1. Model Components, Data Availability and Needs

Model Component	Specific Model Data Elements	General Data Requirements	Data Availability & Sources
CRASH SCENARIOS			
Crash Types	▪ Weighted exposure for rear end crash type or scenario	Relative Incidence of Rear-End Crash Types	▪ Data available using GES (Najm & Smith, 2007)
Pre-Crash Kinematics	▪ Initial headways, and vehicle speeds ▪ Lead vehicle braking level, speed at minimum TTC ▪ Following vehicle braking level, speed at minimum TTC	Distribution of Lead Vehicle Speed & Deceleration Rates	▪ Data available using 100-Car Study
		Distribution of Car Following Headways	▪ Data available using 100-Car Study
		Distribution of Car Following Speeds	▪ Data available using 100-Car Study
Environmental	▪ Day or night ▪ Coefficient of friction (Pavement wet/dry)	Relative Incidence of Crashes by Weather, Day/Night, and other Environmental Factors	▪ Data available using GES (Najm & Smith, 2007)
SIGNAL PARAMETERS			
Conspicuity	▪ Likelihood signal induces following vehicle driver's gaze to lead vehicle when signal is triggered	Data Relating to Signal Eye-Drawing Effects (Attention-Getting) Associated with Various Signal Properties:	▪ Partial data relating signal characteristics to eye-drawing (see below)
		Flashing	▪ Data available Rear Signaling Task1
		Luminance	▪ Partial data relating signal luminance levels to eye-drawing, measured in candela (cd) as the standard unit of luminous intensity
		Expanse	▪
Triggering Criteria	▪ Signal Activation Status (on/off)	Deceleration Level Trigger	▪ Specified as model input
		ABS (Activate Rates)	▪ No data on frequency of ABS activations
		Brake Pedal Activation (General Rate)	▪ Need data on frequency of brake pedal activations

Model Component	Specific Model Data Elements	General Data Requirements	Data Availability & Sources
Appropriateness	▪ Activation in presence of following vehicle (yes/no)	System activation in presence of Rear Vehicle. Specified as model input as Open/Closed Loop System	▪ No data available to define the percentage of "high" deceleration braking events in presence of following vehicle
		Deactivation Criteria (time-based, etc)	▪ Specified as model input
Dis-benefits	▪ Relative incidence of False Positive signal activations ▪ Probability that signal will annoy drivers ▪ Likelihood signal activations result in inappropriate responses from following vehicle drivers and surrounding traffic	False Alarm Rate	▪ No data available on the relative signal activations considered False Positives
		Annoyance	▪ Data available Rear Signaling Task1
		Adverse Reactions	▪ Partial data available from Rear Signaling Task1
DRIVER PARAMETERS			
Attentiveness	▪ Driver gaze at onset of lead vehicle braking (on/off road)	Driver Glance Distributions (on-road, off-road)	▪ Data available using 100-Car Study
Cognitive Workload	▪ Likelihood driver is engaged in secondary task inducing attentional narrowing	Distribution of Secondary Tasks (Likelihood Driver is Engaged in a Distracting Task)	▪ Data available using 100-Car Study
Reaction Data	▪ Driver reaction type, time and magnitude in response to lead vehicle baking event (steering or braking, deceleration levels and duration)	Distribution of Reaction Times	▪ Data available using 100-Car Study
		Distribution of Maneuver Type	▪ Data available using 100-Car Study
		Distribution of Braking Level	▪ Data available using 100-Car Study
		Distribution of Steering Level	▪ Data available using 100-Car Study

Identify Data Needs and Perform Targeted Studies and Activities

As presented above, efforts were undertaken as part of this process to increase available knowledge by identifying and targeting model areas which have little or no available data, and thus are in need of further research and specification. Analytic and empirical activities were defined based on these research needs so that suitable data for model parameters could be generated. For example, effectiveness estimates for an enhanced rear brake signal that uses a deceleration-based trigger would need, as basic input measures, information about the incidence of lead vehicle threshold braking levels, as well as the estimated frequency with which a following vehicle would be present and whose driver is looking away from the road at the onset of lead vehicle braking.

A number of research needs were identified and presented below, with subsequent sections addressing corresponding activities intended to gather needed data and information using a variety of techniques and methods. The number, type, and nature of the prescribed studies performed under project were limited by the available resources. Therefore, although studies were undertaken to support the development of parameter estimates, this work is by no means exhaustive (some areas are in need of further research). Nevertheless, data needs were prioritized so that a sufficient level of data was assembled to populate essential model components, thereby allowing estimates to be generated. Since the model framework is flexible, it can be expanded and updated as new data elements are gathered leading to more robust and reliable effectiveness estimates.

Research to Address Knowledge Gaps

VTTI performed a number of research activities to support model parameter estimates. This work was intended to supplement other research activities performed under this project; specifically Task 1. Additional research activities were performed in order to:

1) Examine the impact of signal luminance on attention-getting (eye-drawing). This study adopted the Unanticipated Event Detection methodology used in the earlier set of "Static Evaluations" and varied lamp luminance levels under both static and flashing signal modes to better understand relationships between lamp luminance, signal mode, and eye-drawing.

2) Examine impacts of following distance on attention-getting (eye-drawing). Previous work examined rear brake signal eye-drawing at distances of 100ft. This study allowed the effects of car following distances on eye-drawing to be assessed at varying distances from the brake signal using the Unanticipated Event Detection methodology.

3) Analyze existing and available datasets to explore the following base rates:
    - Car following situations with following driver glancing off-road (at lead vehicle braking onset)
    - Lead vehicle braking with presence of following vehicle
    - Braking events
    - False Alarm rates based on different system triggering criteria and thresholds
    - Incidence of the conditions under which the rear signaling system is expected to trigger (exposure)

Subsequent Chapters in this report describe and report the results of these research activities.

Chapter 3. Additional Eye-Drawing Studies To Populate Model Parameters

This chapter details a series of empirical studies designed to assess the influence of various signal properties and test conditions on eye-drawing performance – the ability of an enhanced rear brake signal to orient driver's gaze to the lead vehicle following braking onset. The resulting data are used to populate model parameters and expand the range of the effectiveness estimates. These studies complement earlier work performed under Task 1 to define promising brake signal approaches.

Study Purpose & Objectives

Three studies were undertaken –each directed at quantifying the attention-getting capability of various brake signal attributes and signaling approaches. The first was designed to examine a so-called "dual intensity" brake signal approach which prescribes two brake lamp luminance levels using traditional steady-burn signals; one for use during daytime operation, and another for nighttime use. The underlying signal factor studied here relates to signal luminance (or luminance) levels. The second study was closely related to the first and examined different levels of signal luminance under flashing conditions. Thus, signal luminance was studied as a factor under both steady-burn and flashing lamp configurations. The third study examined the effects of viewing distance on the system's ability to draw the eye, and was used to model system performance under different car-following distance configurations. Details relating to each study manipulation and testing conditions are presented below.

1) Examine the impact of signal luminance on attention-getting (eye-drawing) under steady-burn conditions. This study adopted the methodology used in the earlier set of "Static Evaluations" and varied lamp luminance levels (2 levels of luminance) to better understand relationships between lamp luminance and eye-drawing. The main purpose of this experiment was to determine the relationship between signal luminance and eye drawing capability. The data enabled evaluation of the relative effectiveness of a "dual intensity" approach and the performance gains associated with increasing signal luminance levels. Participants were exposed to an Unanticipated Event Detection trial while engaged in a secondary task under static conditions. The specific treatment conditions, levels of on-axis signal luminance, selected for this study included the following (note that all configurations under this study were implemented using a steady-burn pattern - no flashing):

   A. (420 cd) Represents the maximum allowable luminance levels under the current FMVSS108 standard.
   B. (840 cd) Represents 2 times the allowable luminance levels under FMVSS108

   Data for the following luminance level was previously captured under Task 1 evaluations, thereby providing data across a range of three luminance levels.

- □ (130 cd) Represents baseline luminance levels conforming to traditional brake signal light illuminance levels, and the luminance used for the Static Evaluation study undertaken under the Task 1 effort.

2) Examine the impact of signal luminance on attention-getting (eye-drawing) under flashing conditions. This study adopted the methodology used above and varied lamp luminance levels (2 levels of luminance, or luminance) to better understand relationships between lamp luminance and eye-drawing. However, in this study, signal luminance was evaluated in the context of a flashing brake lamp configuration in order to determine the relationship between signal luminance under flashing conditions and eye drawing capability. As in the above study, participants were exposed to an Unanticipated Event Detection trial while engaged in a secondary task under static conditions. The specific treatment conditions, levels of on-axis signal luminance, selected for this study included the following (note that all configurations under this study were implemented using a simultaneous flashing brake lamp pattern, flashing at 5 Hz):

   A. (420 cd) Represents the maximum allowable luminance levels under the current FMVSS108 standard.
   B. (840 cd) Represents 2 times the allowable luminance levels under FMVSS108

   Data for the following luminance levels were previously captured under Task 1 evaluations, thereby providing data across a range of four flashing luminance levels.
   - □ (130 cd) Represents baseline luminance levels conforming to traditional brake signal light illuminance levels, and the luminance used for the Static Evaluation study undertaken under the Task 1 effort.
   - □ (1420 cd) High brighness levels representing over 3 times greater than the maximum allowable photomoetric intensity levels under FMVSS. This corresponds to the "increased luminance" levels used in prior testing

3) Examine the impact of following distance on attention-getting (eye-drawing). Previous work examined several rear lighting configurations at fixed distances of 100 ft. from the lead vehicle (signal light source). This study allowed the effects of car following distances on eye-drawing to be assessed. Given the constraints of the project, a single fixed signaling configuration (simultaneous flashing @ 1420 cd) was selected and tested at varying distances from the light source. Since data for the 100ft condition was previously captured during previous Task 1 evaluations, this study focused on the following two treatment levels: 150 and 200 ft following distances. Evaluations were performed using the same Unanticipated Event Detection methodology as the above two studies.

Test Apparatus

To achieve the experimental setup, a full size appliqué of the rear of a vehicle was mounted to a metal backing. Lamps (consisting of the round 4 diameter LED lights used in previous work) were mounted in arrays in the three locations on the appliqué (for the two outboard lights and the CHMSL). Use of the appliqué concept allowed the testing of LED systems while at the same time not requiring use of an actual vehicle, allowing for a generalized vehicle model. It should be mentioned that at distances of 100 ft (30.5 m) or greater, it was difficult to tell that the experimental setup was not an actual vehicle. The mock-up included working brake lamp units mounted in appropriate locations on the appliqué (one for the CHMSL and two for the two outboard taillights). Software was modified from the earlier LED Optimization and Attention-Getting experiments so that the additional test configurations could be presented with the apparatus.

Figure 5. Vehicle Mock-Up with Working Brake Lamps

Study Design

Evaluations conducted as part of these three studies closely resembled the procedures and methods used in the previous Attention-Getting study conducted as part of this series. Testing was performed with a group of naïve drivers (no previous exposure to the lighting arrays) under static conditions (parked vehicle with individuals not driving the vehicle) in a controlled environment using an instrumented vehicle and the vehicle appliqué mock-up to present the rear signaling configurations. Participants were led to believe the purpose of the study was to evaluate the usability of a commercial in-vehicle navigation system, and were seated in the instrumented vehicle used to administer the navigation tasks, allowing video of the driver's eye gaze as well as the state of the rear lighting signals to be captured.

Uninformed Event Detection Paradigm

Evaluations used an uninformed lighting event detection trials to assess eye-drawing capability for the lighting configurations. Participants (seated in the driver's seat) were asked to complete in-vehicle tasks using an in-car navigation system which caused them to direct their gaze away from the forward roadway. The display and controls were located at a nominal horizontal angle of 30 degrees to the right of the straight forward glance position and then vertically downward at a nominal angle of 18 degrees (Figure 6). Once the driver was engaged in the navigation task (looking away from the forward view) the in-vehicle experimenter issued a signal to activate the lighting array. This was accomplished by having the in-vehicle experimenter signal the confederate experimenter behind the display board (vehicle appliqué concept described previously) using a transmitted radio tone. Care was taken to ensure that the participant did not detect that the experimenter sent the tone. The rear lighting display (vehicle appliqué concept) was straight ahead at a nominal eye to display – with the exception of the third study all data was collected at distance of 100 ft (30.5 m).

In all, there were three triggering events for each participant, all of which occurred without informing the participant. These triggering events occurred as follows: once while receiving instruction but looking at the navigation system display, once when selecting among menu items in the navigation system, and once during text entry into the navigation system. These three events were chosen to reflect increasing levels of visual, cognitive, and manual loading. The number of occurrences of eye-drawing (participants looking-up) and the time it took them to re-direct their gaze forward were measured and served as key dependent measures for assessing eye-drawing capability. Note that obtaining these measures required that a data acquisition system be used to capture time-synchronized video of the participant's (driver's) eye position and the state of the lead vehicle's brake lamps (Refer to Figure 7).

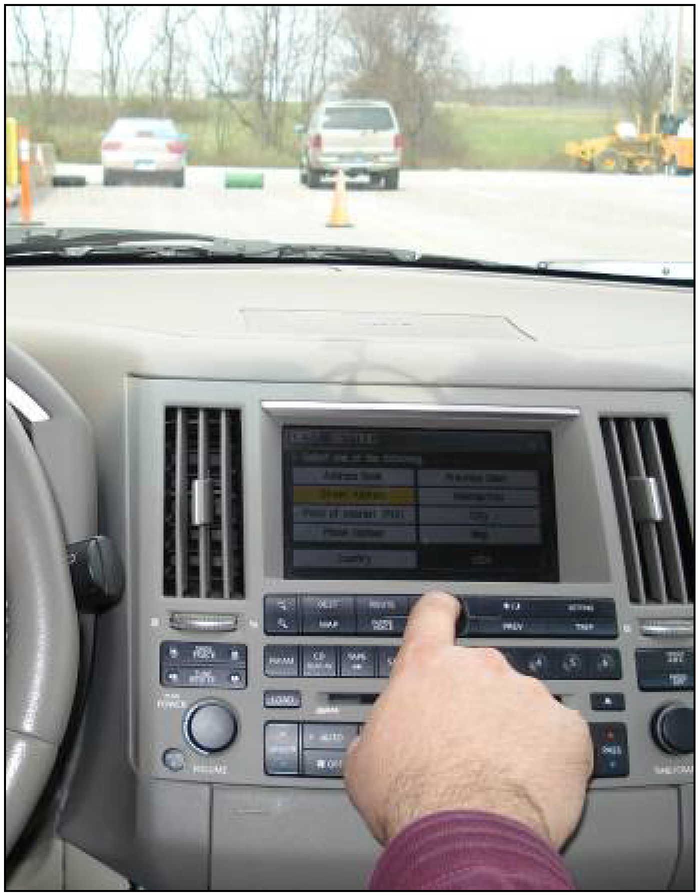

Figure 6. Navigation system in the vehicle used for the uninformed event detection trials

Although participants did not drive the vehicle during the navigation task elements (and therefore had no need to look forward), the hypothesis was that effective signals would compel individuals to redirect their gaze forward. In other words, the eye-drawing capability of some of the signals would cause the driver to look forward even though the need to look forward (as if driving) was not present.

Figure 7. Video from the Instrumented Vehicle Showing Participant Looking Up In Response to the Brake Signal

Participants

In all, 72 participants took part in this phase of the research, distributed across the three experimental studies as shown in Table 2. Candidate participants were screened over the phone with a verbal questionnaire to determine whether they were licensed drivers and whether or not they had any health concerns that might exclude them from participating in the study. Individuals who participated in previous rear signaling studies were considered ineligible to participate.

Table 2. Participant Sample Sizes Across Studies

Study	Participants
1) Signal Luminance Under Steady Burn Lamps - 420 cd (n=10) - 840 cd (n=10)	20
2) Signal Luminance Under Flashing Lamps - 420 cd (n=10) - 840 cd (n=10)	20
3) Following Distance Effects, Flashing @ 1420 cd - 150 ft (n=16) - 200 ft (n=16)	32
Total Sample	72

Data Reduction & Dependent Measures

Performance associated with the uninformed event detection task focused on the lighting configuration's eye-drawing capability as measured by the percentage of drivers glancing forward and the associated latency. In this case, the principal method of data extraction was from the stored video of each event. These video images contained frame numbers which allowed the measurement of elapsed time in responses to the lighting configuration, if any. The recordings indicated when the rear lighting started, and if and when the participant looked up at the forward (vehicle appliqué) display. Consequently, it became possible to determine the duration between signal initiation and the participant's look up response, if any. Driver responses to questions about whether or not they noticed the lighting configurations were also analyzed. The display used a 1 sec brake lighting signal followed immediately by a 5 sec enhanced lighting signal. If the participant did not look up at the display, a value of 6 s was assigned on the assumption that this would be the minimum time in which the participant might have looked up; use of a 6 sec upper boundary also served to limit the influence of cases where the driver failed to detect the signal on the analysis. Thus, all responses were scored as the actual response times or 6 sec if the participant did not respond.

As previously described, there were three exposures to the display lighting as participants worked with the in-car navigation task. Data indexing look-up rates were based on any observed incidence where the driver was observed to glance forward in response to the signal (across any of the exposures). This provided a more relaible means of estimating eye-drawing effects. However, for latency scores only data for the first exposure were analyzed because this situation was totally unanticipated for all participants.

Study Results

Data for each individual study are presented below, with results addressing both eye-drawing percentages and response latency values. Chi-Square tests were used to identify significant differences for eye-drawing percentages, while latency data were analyzed by means of a one-way between-subjects ANOVA.

Study 1: Signal Luminance Under Steady Burn Lamps

As shown in Figure 8, increasing luminance to 420 and 840 cd under the steady burn configuration led to little performance gains relative to baseline luminance levels; detection rates increased by 10% for the 840 cd condition – levels which were not statistically significant from the baseline. As shown in Figure 9, reponse latencies for both treatment conditions also were not signficantly different from baseline performance; the average latency for the 840 cd condition was approximately 5.49 sec to respond compared to 6.00 sec under baseline lighting levels (bars in the graph with the same letter designations are not statistically different).

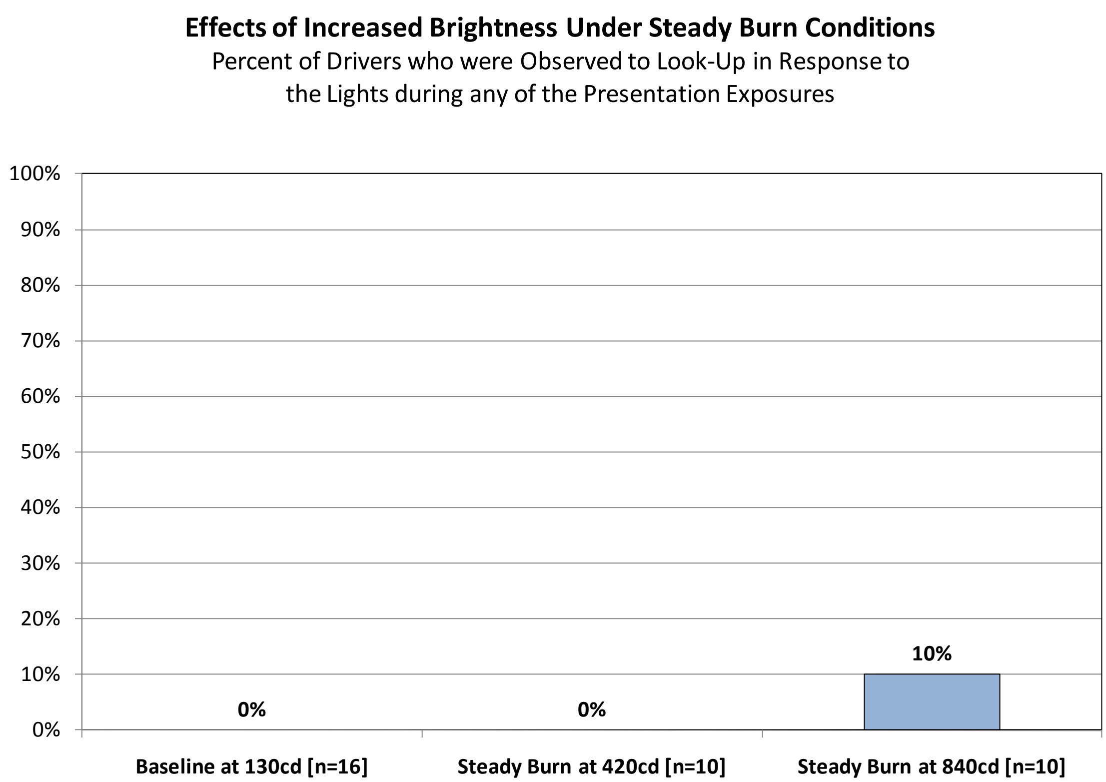

Figure 8. Eye-Drawing Effects for Increased Luminance (Brightness), Steady Burn Conditions

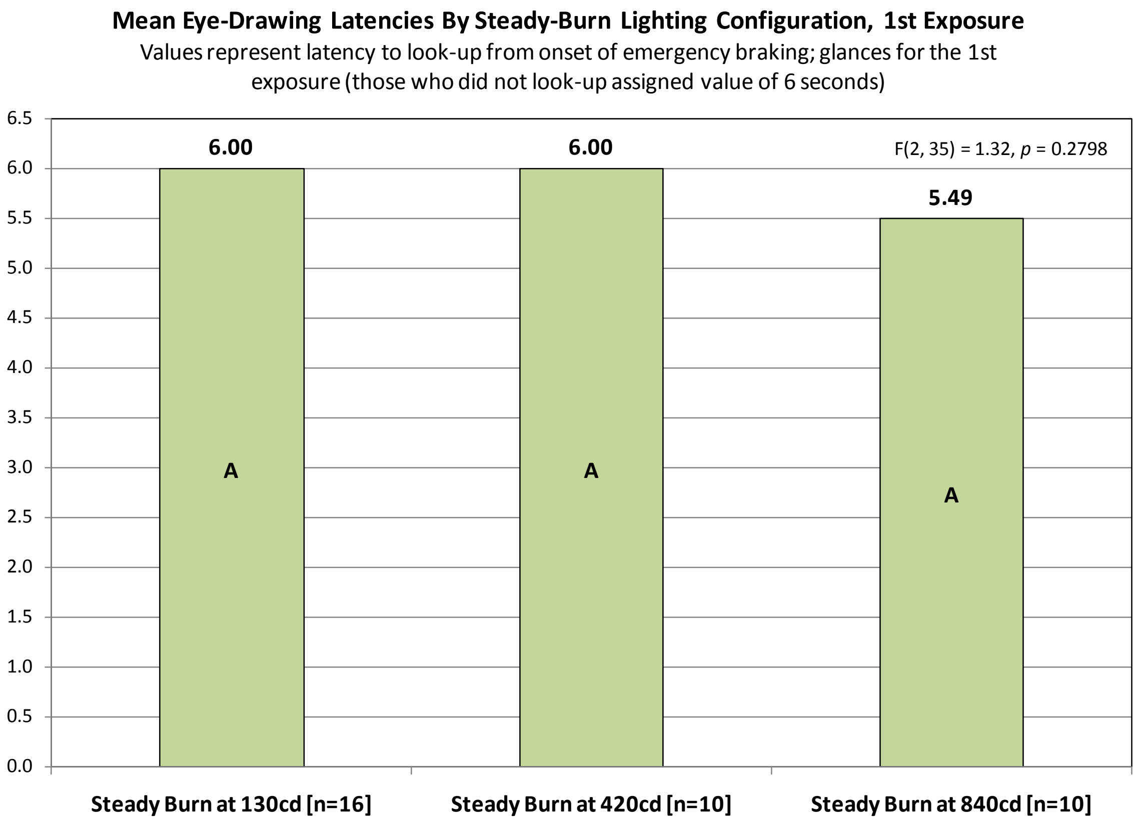

Figure 9. Response Latency Effects for Increased Luminance, Steady Burn Conditions

Study 2: Signal Luminance Under Flashing Lamps

In contrast to its steady-burn counterpart, increased luminance levels under the flashing lamp configurations led to substanital performance gains. As shown in Figure 10, increasing luminance to 420 and 840 cd with the flashing lamps increased detection performance to 70% - levels comparable to that achieved with the most extreme luminance manipulation of 1420 cd tested in prior work. As shown in Figure 11, reponse latencies for both treatment conditions were faster relative to baseline configuration (steady burn @ 130 cd), with performance averaging approximately 3.02 sec under 420 cd, and 3.46 sec under 840 cd compared to 6.00 sec under the baseline condition. Note that the pattern shows a slight, non-significant, increase in reponse times with increasing luminance levels; these results may be an artifact of the smaller sample sizes and large variation in two of the conditions. Only the latencies associated with the 420 cd condition were significantly faster than baseline; however, the three increased luminance conditions were not statistically different from each other (bars in the graph with the same letter designations are not statistically different).

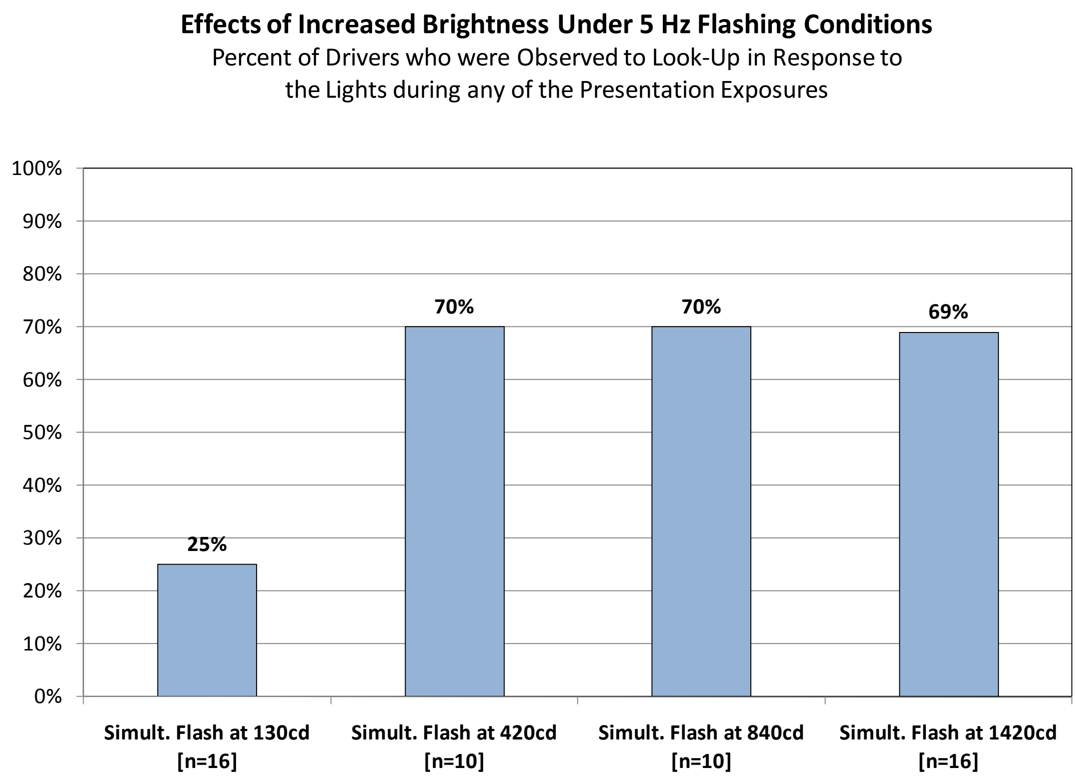

Figure 10. Eye-Drawing Effects for Increased Luminance (Brightness) Flashing Lamp Conditions

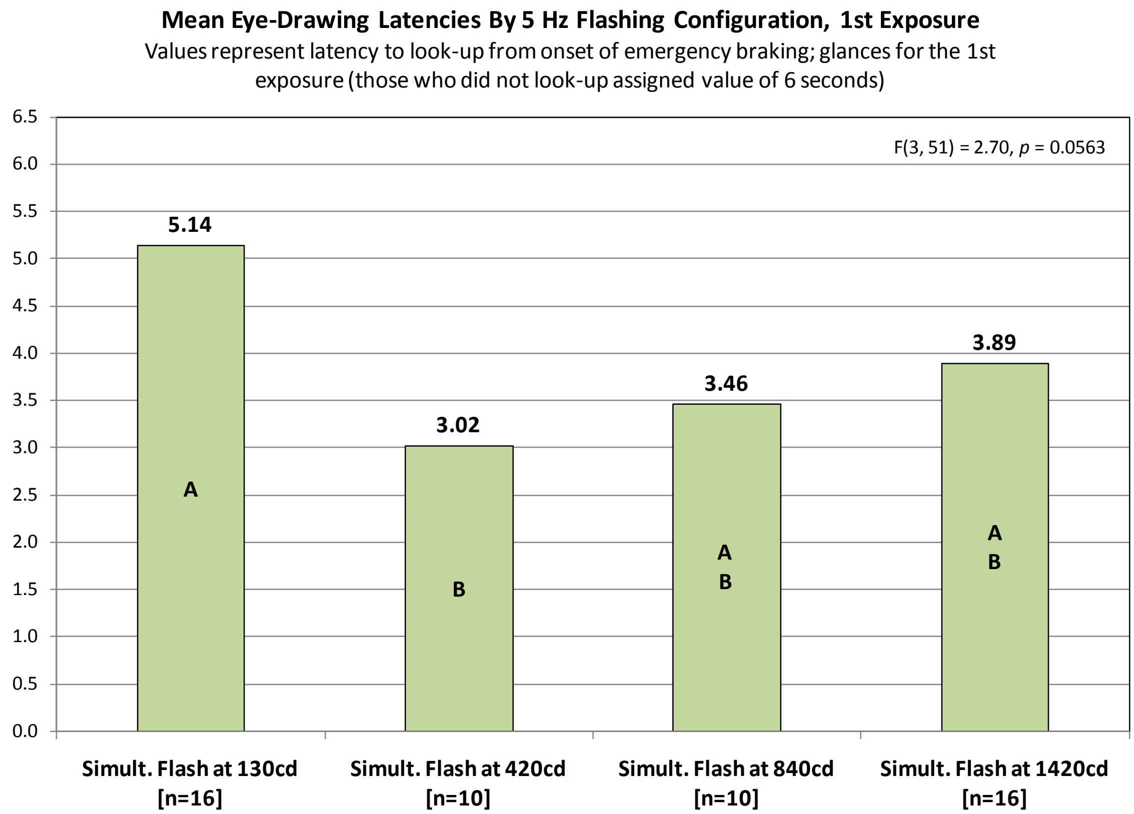

Figure 11. Response Latencies for Increased Luminance Flashing Lamp Conditions

Study 3: Effect of Distance on Signal Detection

Distance from the signal source was varied in order to estimate the influence of following distance on signal detection rates; this study used a single fixed brake lamp configuration of simultaneous flashing at 5Hz under high luminance (1420 cd). As shown in Figure 12, increasing distance from the signal source led to a slight, but non-significant drop in detection performance at 150 ft; dropping from 69% at 100 ft to 63% at 150 ft (equivalent to 1.7 sec and 1.4 sec headway at 60mph, respectively). Detection performance signficantly deteriorated at 200 ft. where rates fell to a low of 25% detection (equivalent to a 2.7 sec headway traveling at 60 mph). Response latencies followed a similar pattern with response latencies increasing as distances from the signal increased; response latencies increased from an average of 3.04 sec at 100 ft. to 4.06 sec at 150 ft, and 5.35 sec at 200 ft. Nevertheless, observed differences among these groups did not reach statistically significant levels (bars in the graph with the same letter designations are not statistically different).

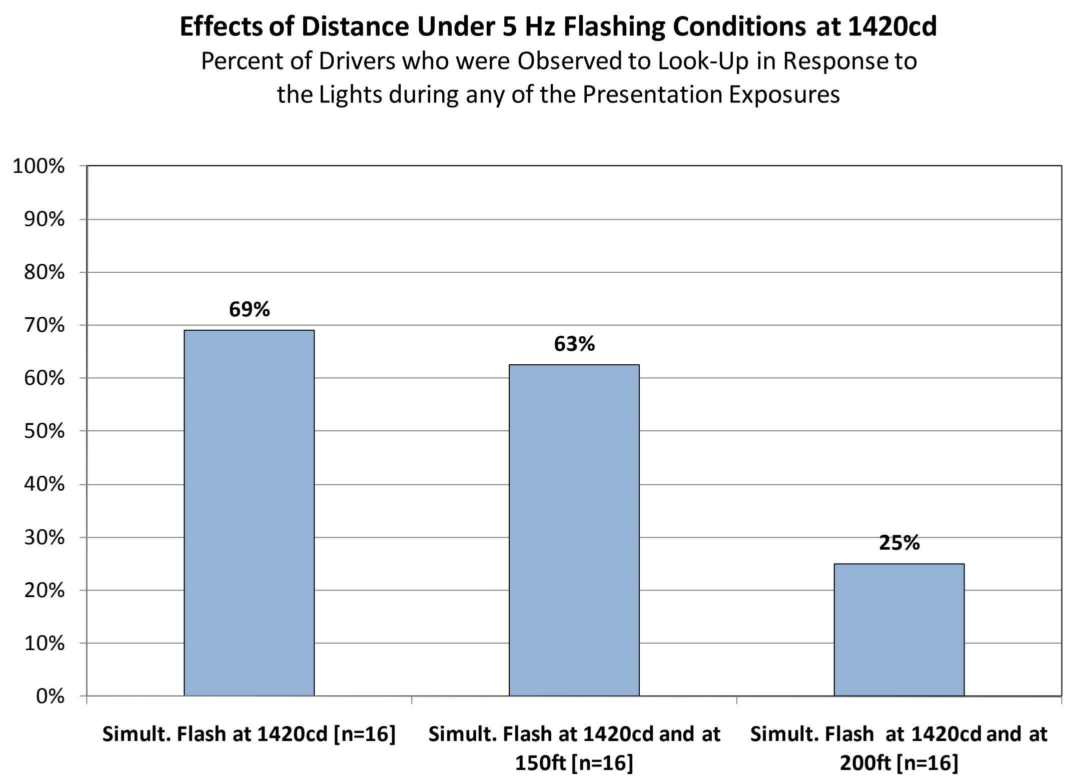

Figure 12. Effects of Distance on Signal Detection Under Flashing at 1420cd

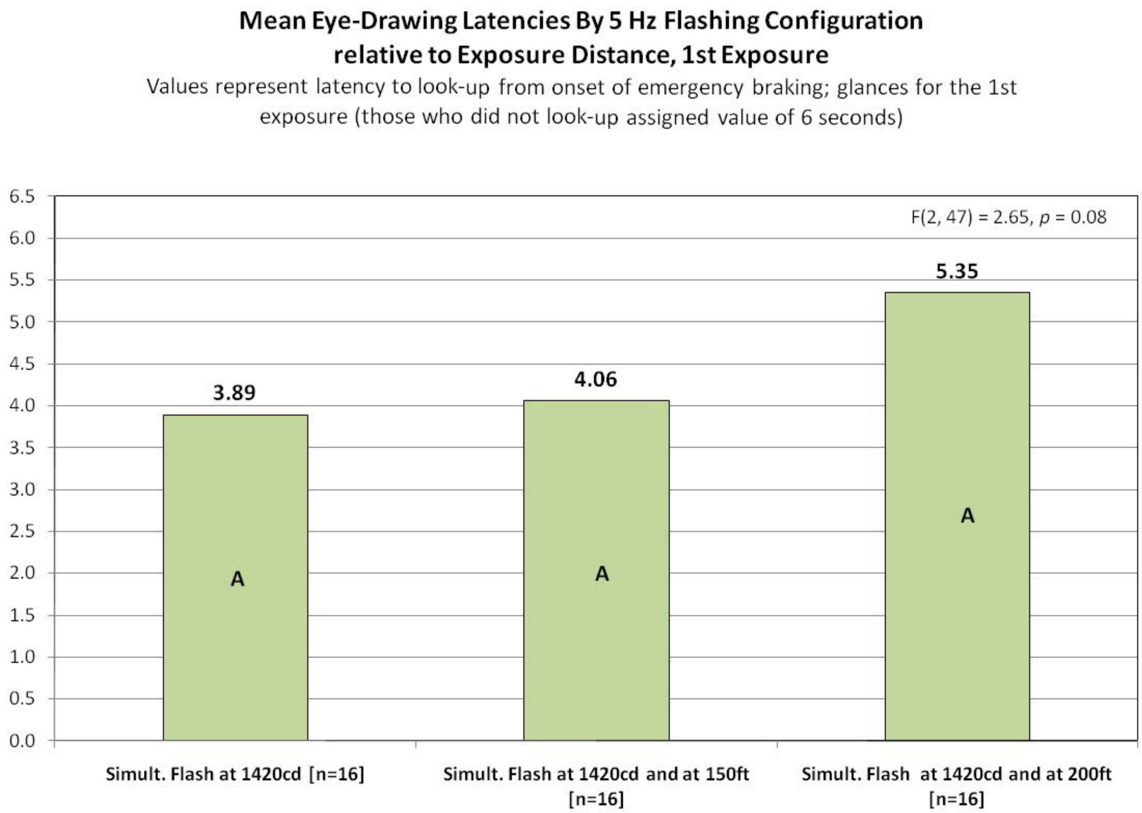

Figure 13. Response Latency Effects of Distance on Signal Detection Under Flashing at 1420cd

Summary of Integrated Study Results

Several experiments were conducted under this project using the Uninformed Event Detection method, including the set of three studies presented and discussed above, as well as previous work under Task 1 which led to the identification of promising LED signal approaches. Data captured as part of this effort, characterizing signal detection rates and response latencies, contributed to the development of the rear signaling model by identifying the impact of key signal parameters such as effects of signal type, luminance, flashing, and distance. Studies yielded two key performance measures (detection rates and response latencies), both of which were input into the simulation model in the form of parameter estimates. Figure 14 summarizes the observed detection rates across key signal and test conditions, and Figure 15 illustrates the associated reponse latencies indexing the average time it took participants to look up in response to the signal. Since participants in these studies were not actually driving, latency values were transformed into more meaningful units expressed as a percentage indexing the relative improvement in response times compared to performance under the baseline condition (steady burn @130 cd); values are plotted in Figure 16.

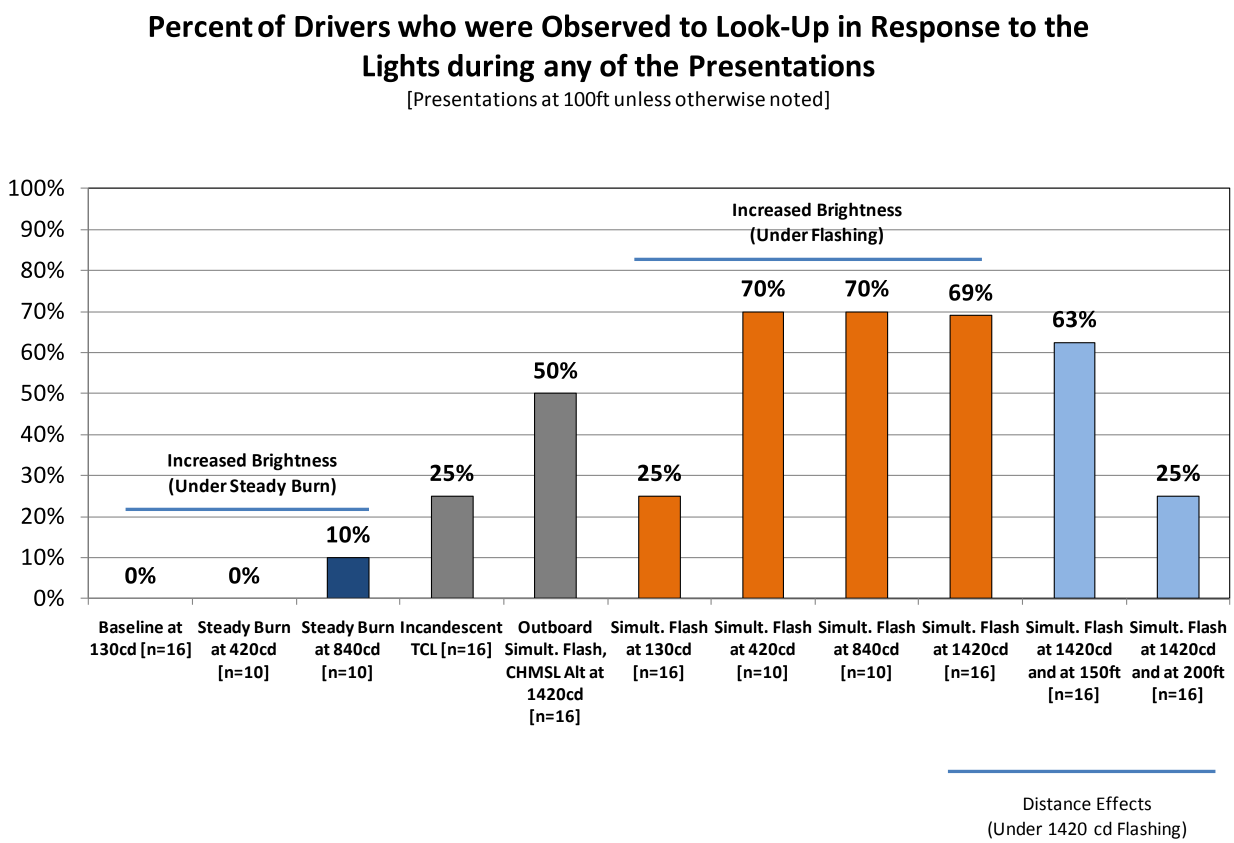

Figure 14. Summary of Detection Rates Across Rear Brake Signal Conditions

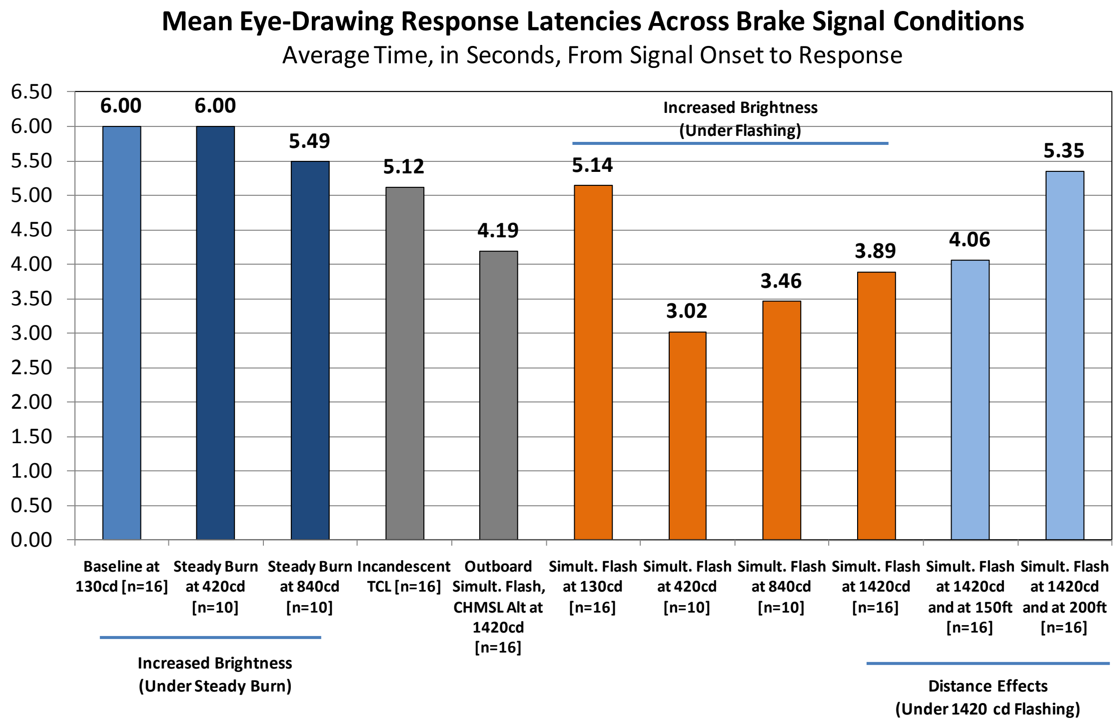

Figure 15. Mean Response Latencies Across Experimental Conditions

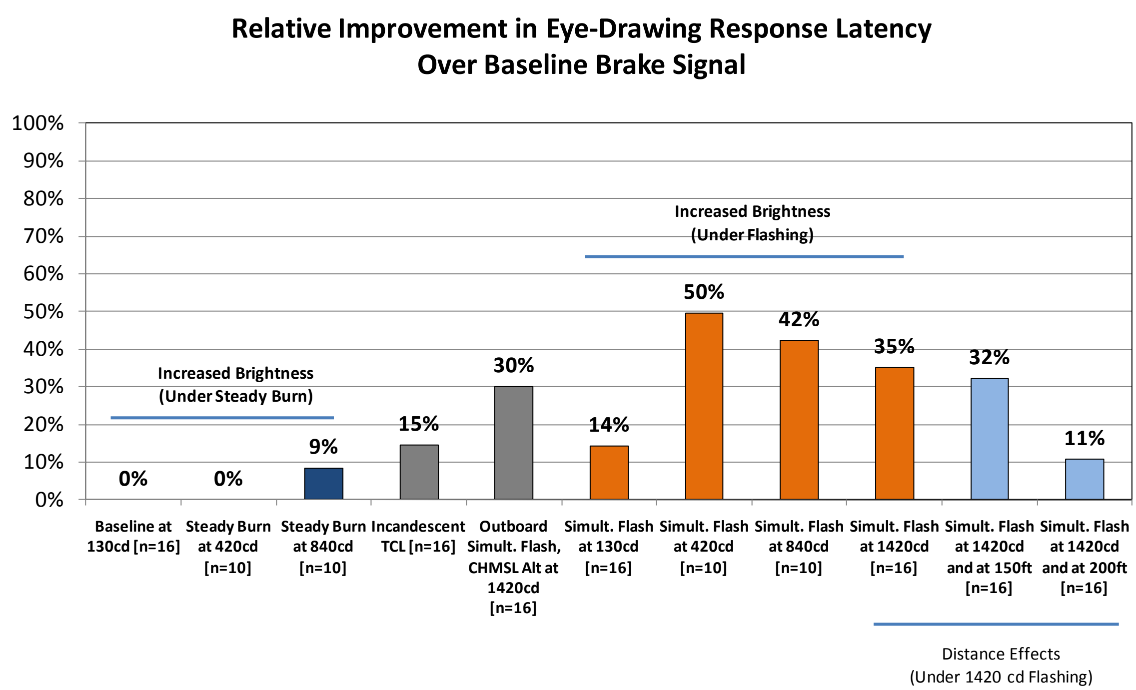

Figure 16. Relative Improvement in Response Latencies Across Experimental Treatments

Together, these graphs illustrate several key findings of relevance to the development and implementation of effective brake signals as well as to the simulatiom model, including the following:

- Increases in brake signal luminance (brightness levels) do not necessarily translate into increased signal detection or faster response times; effectiveness appears to be moderated by signal type, among other factors. Increases in brake lamp illumination resulted in little or no improvement under steady-burn lamp configurations, yet demonstrated significant gains in detection performance under flashing lamp configurations. This suggests that increasing the luminanceof conventional steady-burn brake lamps does not appear to be an effective means of drawing attention to the brake signal; no performance gains were osberved at luminance levels of 420 cd, and only minimal gains were observed at luminance levels of 840 cd – twice the maximum allowable level under FMVSS.

- Substantial performance gains may be realized by increasing brake lamp luminance levels under flashing configurations; however, increases beyond a certain luminance threshold will not return substantive performance gains. Data found that detection rates under the 5Hz flashing lamp configurations increased to approximately 70% when luminance levels were increased to 420 cd – the current maximum luminance level allowable under FMVSS. No additional increase in signal detection was observed at illumination levels of 840 cd and 1420cd, suggesting that "attention-getting" (or , the ability to draw the driver's attention to brake signal) does not respond in a linear fashion to changes in luminance.

- Signal viewing distance also appears to moderate detection performance, particularly at longer distances out to 200 ft. Signal effectiveness (measured here in terms of detection rate) for the simultaneous flashing condition at maximum luminance (1420 cd) dropped slightly to 63% at150 ft from the signal source, and fell sharply at 200 ft where detection rates of 25% were observed. This suggests that detection rates may remain fairly stable out to distances of 150 ft (equivalent to a 1.7 sec headway traveling at 60 mph), but can be expected to drop at distances beyond this range.

Chapter 4. Model Data Parameters & Sources

The Safety Impact Methodology (SIM) model used the available empirical data to derive estimates of safety benefits. The model was implemented in Matlab and is composed of three sections. First, the control code, which defines the simulation parameters, calls the simulation model, and converts the output of the simulation model into safety benefits estimates. Second, the simulation model, which is implemented in Matlab's Simulink language and models an independent lead-vehicle-braking conflict every time it is accessed with appropriate parameters. Third, within the simulation model, a series of indicator graphs that show what occurs at each simulation step for each independent lead-vehicle-braking conflict.

The SIM model is described in this section. The discussion follows the typical flow of a SIM model execution. Results obtained by running the model using a number of different enhanced signaling and situational parameters are described at the end of this section.

The following two sub-sections described the different parameters that are used to run the Monte Carlo simulation and obtain the outcomes (e.g. crash, no crash) and descriptors (e.g., speed at impact) that will be used later in calculating the benefits of the different potential countermeasures. These parameters constrain, probabilistically, the set of scenarios that are considered in the simulation.

Data Parameters

The first step in the model is to define a number of constants and distributions that are used later within the simulation model. The first variable defined is *ScenarioGen*, which is set to 1 if random selection amongst possible scenarios will be allowed for the model execution. This random selection is made from the variable *PossibleScenarios*, which is equal to 1 for any scenario that will be considered in the run. In the current simulation, only a rear-end crash with lead vehicle in motion or stopped for less than 2 sec is modeled. Therefore, even though the default value for *ScenarioGen* is 1, there is only one scenario defined as possible within *PossibleScenarios*.

The next variables (*Perc11* and *Perc6*) define percentile values to be used in interpolating the different distributions. Some distributions used in the model could only be defined in coarser terms (Min, 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th}, Max; represented in *Perc6*), whereas others could be defined in intervals of ten percentile points (Min, 10^{th}, 20^{th}, 30^{th}, 40^{th}, 50^{th}, 60^{th}, 70^{th}, 80^{th}, 90^{th}, Max; represented in *Perc11*). *Perc6* and *Perc11* provided the model with the percentile values that were represented by different values organized in the matrices described in most of Table 3 so that, when necessary, appropriate interpolations could be made. *Perc6*=[0; 0.10; 0.25; 0.50; 0.75; 0.90; 1]; *Perc11*=[0; 0.10; 0.20; 0.30; 0.40; 0.50; 0.60; 0.70; 0.80; 0.90; 1].

The next section of the code defines the distributions of driver behaviors. Three distributions were defined, one for instances where the behavior preceded a crash, one where it preceded a Near Crash, and one where it preceded a Crash-Relevant Conflict. These distributions were all obtained from the 100 Car database (Lee, Llaneras, Klauer, and Sudweeks, 2007). Separation of events into these categories followed the 100 Car classification. Different distributions were obtained for each event category because the factors being considered have an influence on the outcome of the event. For example, it is logical that longer reaction times would be present in instances where a crash occurred. Therefore, it was considered appropriate to implicitly consider this interaction by separating distributions of the different measures based on the event outcome.

Proportions were calculated based on the frequency of each of these types of conflicts within the dataset, and used in the simulation to pick values from each category proportionally to their presence. Note that for reaction time, proportions were also calculated that define how often that reaction time was zero, implying that the driver was already braking when the conflict occurred. The variable names and values are shown on Table 3.

Table 3. Driver model variables.

Variable Name	Value	Function/Notes
Crash, Near Crash, and Crash Relevant Conflicts Proportions		
CrashRTProportion CrashAverageAccelProportion CrashPeakAccelProportion CrashHeadwayProportion CrashFollowSpeedProportion CrashTTCProportion	0.0024	Proportion of conflicts that will be selected from the distributions for each category.
NearCrashRTProportion NearCrashAverageAccelProportion NearCrashPeakAccelProportion NearCrashHeadwayProportion NearCrashFollowSpeedProportion NearCrashTTCProportion	0.0617	
CrashConflictRTProportion CrashConflictAverageAccelProportion CrashConflictPeakAccelProportion CrashConflictHeadwayProportion CrashConflictFollowSpeedProportion CrashConflictTTCProportion	0.9359	
Reaction Time		
CrashZeroRTProportion	0.3333	Proportion of each type of conflict that had a reaction time of zero (driver already reacting when conflict began)
NearCrashZeroRTProportion	0.2474	
CrashConflictZeroRTProportion	0.3307	
CrashRT	[1.10; 1.80; 2.26; 2.52; 2.66; 3.00; 3.36; 3.57; 4.92; 5.83; 5.90]	Reaction time distributions. Refer to *Perc11* for the percentiles corresponding to each value.
NearCrashRT	[0.10; 0.40; 0.70; 1.00; 1.40; 1.70; 1.9; 2.1; 2.66; 3.7; 12.10]	
CrashConflictRT	[0.10; 0.40; 0.70; 1.00; 1.30; 1.50; 1.8; 2.2; 2.7; 3.5; 15.50]	
Average Acceleration		

CrashAverageAccel	[-0.30; -0.26; -0.23; -0.20; -0.17; -0.07; -0.07; -0.07; -0.06; -0.05; -0.03]	Average acceleration distributions. Refer to *Perc11* for the percentiles corresponding to each value.
NearCrashAverageAccel	[-0.67; -0.44; -0.39; -0.34; -0.31; -0.19; -0.23; -0.19; -0.14; -0.10; 0.00]	
CrashConflictAverageAccel	[-0.63; -0.37; -0.33; -0.30; -0.27; -0.20; -0.23; -0.20; -0.17; -0.12; 0.00]	
Peak Acceleration		
CrashPeakAccel	[-0.93; -0.87; -0.82; -0.77; -0.66; -0.63; -0.58; -0.53; -0.47; -0.43; -0.40]	Peak acceleration distributions. Refer to *Perc11* for the percentiles corresponding to each value.
NearCrashPeakAccel	[-0.98; -0.89; -0.82; -0.78; -0.72; -0.69; -0.63; -0.58; -0.52; -0.42; -0.05]	
CrashConflictPeakAccel	[-0.96; -0.66; -0.59; -0.56; -0.53; -0.52; -0.47; -0.44; -0.42; -0.40; 0.00]	
Initial Headway		
CrashHeadway	[0.25; 0.30; 0.55; 1.46; 2.38; 3.52; 4.00]	Headway distributions. Refer to *Perc6* for the percentiles corresponding to each value.
NearCrashHeadway	[0.25; 0.58; 0.82; 1.22; 2.05; 3.19; 4.00]	
CrashConflictHeadway	[0.25; 0.65; 0.95; 1.49; 2.33; 3.60; 4.00]	
Initial Following Vehicle Speed		
CrashFollowSpeed	[3.31; 11.41; 14.34; 17.42; 19.94; 22.19; 25.67; 29.16; 34.99; 40.39; 62.76]	Initial following vehicle speed distributions. Refer to *Perc11* for the percentiles corresponding to each value.
NearCrashFollowSpeed	[3.31; 11.41; 14.34; 17.42; 19.94; 22.19; 25.67; 29.16; 34.99; 40.39; 62.76]	
CrashConflictFollowSpeed	[3.37; 11.77; 14.79; 17.38; 19.94; 22.65; 25.35; 29.25; 34.50; 40.39; 74.89]	
Initial Time-to-Collision (TTC)		
CrashTTC	[0.50; 0.63; 1.18; 1.65; 3.91; 6.32; 6.50]	Initial TTC distributions. Refer to *Perc6* for the percentiles corresponding to each value.
NearCrashTTC	[0.50; 0.58; 0.82; 1.22; 2.05; 3.19; 3.50]	
CrashConflictTTC	[0.50; 0.65; 0.95; 1.49; 2.33; 3.60; 4.00]	

Driver Response to Signals

The next parameters defined in the model are those that will determine how drivers respond to the countermeasure. These parameters were derived from the empirical tests conducted with naïve subjects as part of this project. Results from these tests were incorporated in the model via two variables. The first one, *EyeDrawing*, specifies the probability that the lead vehicle driver's attention will be drawn to the forward scene relative to a standard brake light. There are five factors that modulate this probability:

- Light pattern: Steady, Traffic Clearing Light (TCL), Flashing
- Luminance: 130 cd, 420 cd, 840 cd, 1420 cd
- Height: Standard brake lamp location, Center High-Mount Stop Light (CHMSL)
- Distance: 100 ft, 150 ft, 200 ft
- Time of Day: Day, Night

EyeDrawing is initialized to zeros, and portions are filled in based on the available data. Note that data are not available for all cells. The following describes the data that are available:

- Steady burn, Standard brake lamp location, 100 ft, Day; as a function of lamp luminance (i.e., 130 cd, 420 cd, 840 cd, 1420 cd): [0,0,0.10,0]
- TCL, 100 ft, Day; CHMSL-height; as a function of lamp luminance and height: [0,0,0,0.25]
- Flashing, 100 ft, Day; as a function of lamp luminance and height: Standard - [0.25,0.695,0.695,0.695]; CHMSL - [0,0,0,0.50] (Note that the values for the three brightest flashing conditions were pooled due to a lack of statistical significance between the groups)
- 150 ft distance: 90.6% of the value at 100 ft
- 200 ft distance: 36.0% of the value at 100 ft
- Day and night have the same values due to lack of nighttime data

The second variable used to incorporate empirical test results was *ReactionReduction*, which indicated the percentage reduction in reaction time (based on the response latency measures discussed in Chapter 3) with an enhanced signal compared to a standard signal. The five factors that modulate this percentage reduction are the same ones that were used to modulate the *EyeDrawing* proportion. *ReactionReduction* is initialized to zeros, and portions are filled in based on the available data. Note that data are not available for all cells. The following describes the data that are available:

- Steady burn, Standard brake lamp location, 100 ft, Day; as a function of lamp luminance: [0, 0, 9%, 0]
- TCL, 100 ft, Day; CHMSL-height; as a function of lamp luminance and height: [0,0,0,15%]
- Flashing, 100 ft, Day; as a function of lamp luminance and height: Standard - [14%,40%,40%,40%]; CHMSL - [0,0,0,30%] (Note that the values for the three brightest flashing conditions were pooled due to a lack of statistical significance between the groups)
- 150 ft distance: 80.0% of the value at 100 ft
- 200 ft distance: 27.5% of the value at 100 ft
- Day and night have the same values due to lack of nighttime data

Signal Activation

The next parameters defined are those that control the signal activation, which can be controlled by the following parameters:

- Simple activation threshold (*ActivationThreshold*): signal always activates if this deceleration parameter is exceeded. Default value: 0.35g.
- ABS activation (*ABSTriggerActive*): signal always activates if ABS is active. Parameter is 1 if this activation criterion should be used. Default value: 0.
- Closed-loop activation (*TTCTriggerActive*): signal always activates if a minimum TTC threshold is exceeded. Parameter is 1 if this activation criterion should be used. Default value: 0. If the activation criterion is used, the threshold value for activation is stored in *TTCActivationParameter*, which has a default value of 1.5 sec.
- Signal activation timeout (*SignalTimeout*): maintains the signal on for a set amount of time after initial activation. Default value: infinity (i.e., until the lead vehicle brake pedal is released, but the simulation is designed to end before this happens).
- Time of day (*DayorNightTrigger*): used to simulate instances where different system properties are available during daytime compared to nighttime. Parameter is 1 if this modulation factor should be used. Default value: 0.
- *Appropriateness*: whether the signal activation is appropriate. Parameter represents the probability of appropriateness. Default value: 1 (i.e., always appropriate).
- *Disbenefits*: whether the signal activation generates an inappropriate response from the following vehicle driver. Parameter represents the probability of inappropriate response. Default value: 0 (i.e., no inappropriate responses).

The final set of pre-defined general parameters describe the maximum braking attainable as a function of environmental conditions. *WetPavementBraking* defines maximum braking on wet pavement conditions (Default value: 0.65g). *DryPavementBraking* defines maximum braking on dry pavement conditions (Default value: 0.90g).

Definition of Simulation Control and Scenario-Variant Parameters

The next section of the control code defines the simulation control parameters. There are four of these parameters:

- *MaxTime*: defines the maximum time the simulation will run. Default value: 90 sec (which will not limit simulation outcome but will prevent the simulation from running indefinitely if model settings do not allow a conflict to occur).

- *NumberofRuns*: sets the number of independent runs that will be used to calculate the safety benefits. Runs are composed of iterations (see below). Multiple numbers of runs are used to allow for the calculation of statistical confidence around the safety benefits estimates obtained from the simulation.
- *NumberofIterations*: sets the number of independent iterations that will be used to calculate the summary of outcomes for each run. Each iteration is an independent simulation of a lead-vehicle-deceleration (or lead-vehicle-stopped for less than 2 sec) conflict. Default value: 1000.
- *wholeindex*: controls whether the simulation runs are being evaluated with the enhanced signal system active or with standard brake lamps. Each evaluation of an enhanced signal system needs to be compared to a matched evaluation of a standard brake lamp in order to calculate safety benefits.

Once the simulation control parameters are defined, the control code defines the characteristics of the enhanced signal that is being assessed. There are three characteristics that must be defined:

- *Luminaire*: 0 - Steady Burn; 1 - TCL; 2 – Flashing
- *Luminance*: 0 - 130cd; 1 - 420 cd; 2 - 840 cd; 3 - 1420 cd
- *Location*: 0 - Standard brake lamp location; 1 – CHMSL

In each analysis using the SIM, all three of these values are set to zero when the simulation is assessing performance of the standard lamp system.

At this point, the control code begins the loop that will produce each of the independent runs. The random number generator is initialized to a different value for each run; that value is a function of the computer time, which is non-repeating.

Once the random number generator is initialized, the loop that controls each of the iterations within a run begins. The first step in this loop is to select the scenario that will be simulated for the iteration. Note that in the current model, a single scenario sufficed to encompass the majority of the crash problem addressable by these enhanced rear signals. Therefore, the selected scenario is always the same. The scenario selected is stored in the *SelectedScenarios* variable.

The next step in the control code is to pick values from distributions (discussed previously, as part of the "Definition of constants" section) as needed to fully represent the initial kinematics and environment of the situation being modeled. The values selected are stored in the following variables:

- *TimeofDay*: generates day and night cases in the model proportionally to their representation in rear end crashes. A value of 1 represents nighttime. The variable assumes that 79.7% of these types of crashes occur in the daytime (based on analysis of GES data).

- *WetorDry*: generates wet and dry pavement cases in the model proportionally to their representation in rear end crashes. A value of 1 represents dry conditions. The variable assumes that 18.2% of these types of crashes occur in wet conditions.
- *PeakLeadVehicleDecelerationRate*: peak deceleration for the lead vehicle; uniformly distributed between 0.50 and 0.90 g.
- *AverageLeadVehicleDecelerationRate*: average deceleration for the lead vehicle; uniformly distributed between 0.50 and the PeakLeadVehicleDecelerationRate.
- *InitialHeadway*: initial headway between lead and following vehicles, in seconds.
- *FollowingVehicleInitialSpeed*: initial speed for the following vehicle; in m/sec.
- *InitialTTC*: initial TTC between lead and following vehicles, in seconds.
- *LeadVehicleInitialSpeed*: initial speed for the following vehicle; in m/sec. Calculated based on the following vehicle initial speed, initial headway, and initial TTC.
- *ReactionTimeDistribution*: reaction time that the following vehicle driver will incur in after the lead vehicle starts braking; in sec.
- *PeakAccelDistribution*: peak deceleration that will be available to the following vehicle's driver; in g.
- *AverageAccelDistribution*: average deceleration that will be available to the following vehicle's driver; in g.

The control code then proceeds to define some parameters related to driver behavior and actions, as follows:

- *ForwardGlanceProbability*: likelihood that the driver is glancing forward when the conflict starts. A value of 1 represents a forward glance when the conflict starts. The assumption in setting this value is that 68.5% of these types of crashes occur when glances are not initially directed forward, which is based in 100 Car study data.
- *SecondaryTaskEngagement*: likelihood that the driver is performing a secondary task. A value of 1 indicates that a secondary task is not being performed. The assumption in setting this value is that 26% of these types of crashes occur when drivers are engaged on a secondary task.
- *ManeuverTypeDistribution*: type of following driver reaction to the conflict. A value of 0 indicates braking. The assumption in setting this value is that all maneuvers involve only braking. Analyses of 100 Car study data suggest that only 4.7% of these conflicts involve steering without braking.
- *PeakYawRateDistribution*: Variable is not used, since there are no steering maneuvers.
- *AverageYawRateDistribution*: Variable is not used, since there are no steering maneuvers.

- *LookForwardCorrection*: Calculates a reduction in reaction time that is used when the following vehicle driver is looking forward. That reduction is assumed to follow a uniform distribution between 0 and 0.25 sec (assumed).
- *FollowingVehicleJerk*: Defines the jerk that the following vehicle will generate while braking. Default value: 0.5 g/sec.

At this point in the process, the control code has defined all the parameters that the simulation needs in order to execute. The next step in the control code is to execute the simulation model.

Simulation Model

The purpose of this section is to provide the reader with a high-level overview of the structure of the simulation model and the transformations that are necessary to obtain the data used in the calculation of system benefits. The reader that is interested in details about the transformations that occur is referred to the simulation, and the annotated simulation control code. Figure 17 shows the top level of the simulation model which is composed of three main modules or subsystems:

1. *Signal Parameters*: defines the properties of the enhanced signal being evaluated
2. *Crash Scenario Definition*: establishes the kinematic characteristics of the scenario that will be simulated by selecting randomly from the distributions of variables related to the scenario kinematics for each iteration
3. *System Simulation Model*: processes the simulation until an outcome is achieved and collects information about the outcomes and characteristics of each iteration for output to the control code

Subsystems 1 and 2 in the previous figure are straightforward in that their only function is to input values from the control code in the simulation and pass them along to other subsystems. They won't be discussed in further detail, as descriptions for the estimation of these values have already been provided. Subsystem 3, however, is more complex, as it performs most of the core calculations that allow the simulation to function. Its main components are shown in Figure 18.

There are three main components for this subsystem, as follows:

- 3.1.1 – This module determines whether kinematic conditions warrant the activation of the enhanced signal. It also calculates the probabilities of various outcomes related to that signal, specifically, the probability that the reaction time will be reduced and the probability that the enhanced signal draws the following vehicle driver's eye, which translates into an avoidance of reaction times over certain thresholds.

- 3.1.2 – Processes initial scenario characteristics. Apart from passing along a number of parameters that are provided from the control code, its main function is to generate the lead vehicle's deceleration profile, which is assumed to always follow a triangular shape with a peak at a predetermined peak deceleration and equal slopes to and from the peak. The slopes are determined based on the time that the braking maneuver will take, assuming a constant deceleration value.

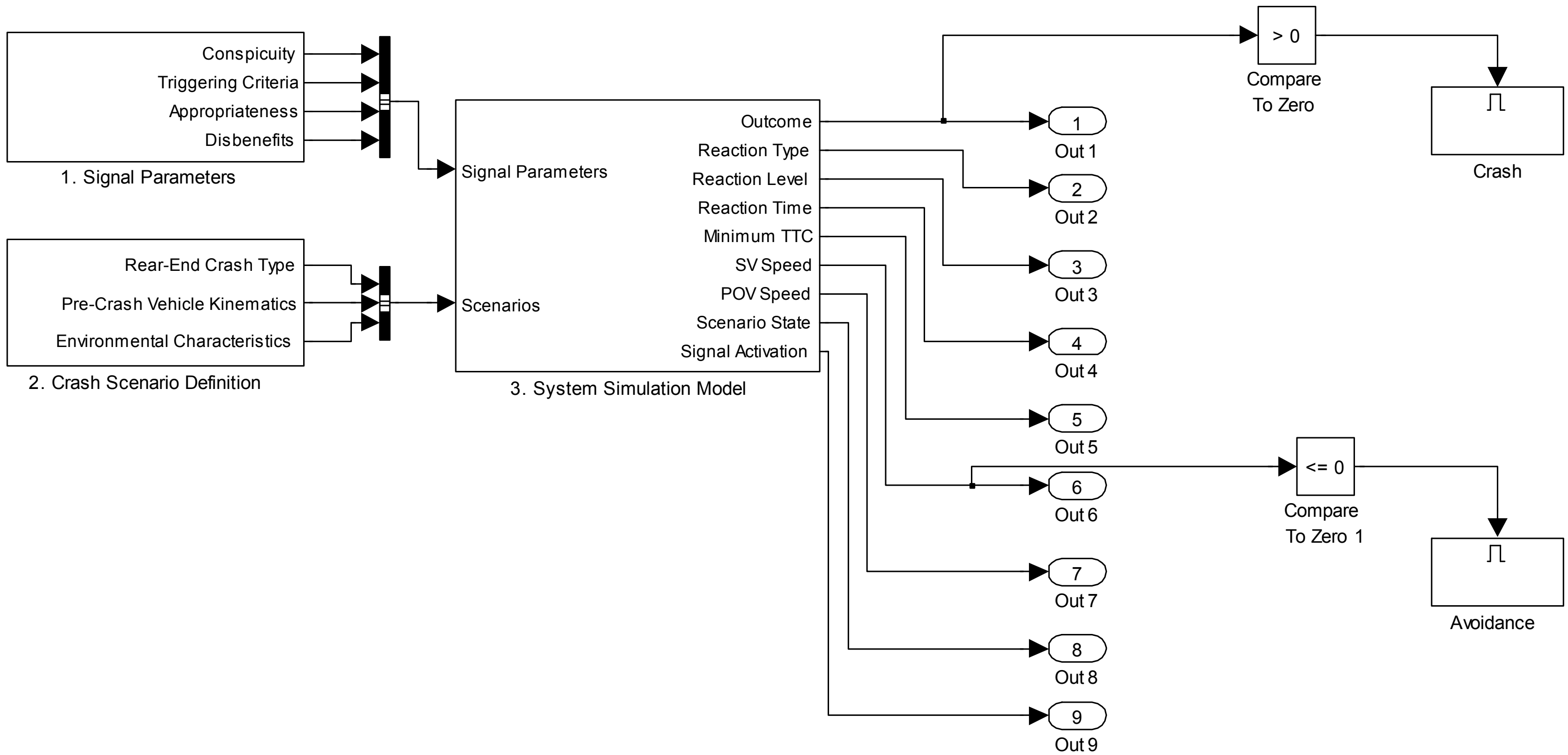

Figure 17. Simulation model core.

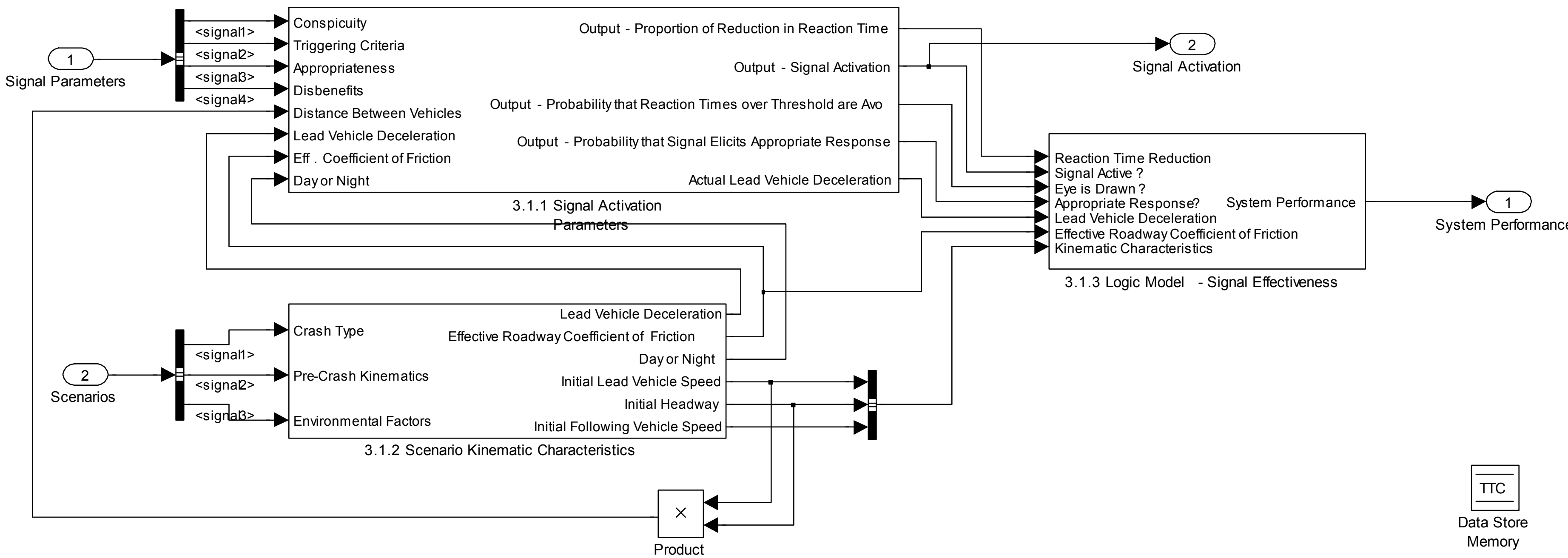

Figure 18. Depiction of the model structures within module 3 in the core layer of the model.

3.1.3 – Calculates the effectiveness of the enhanced signal activation in preventing/reducing the severity of a crash.

- Figure 19 shows this module. It has two main components. Component 3.1.3.1 takes all the inputs related to driver behavior and combines them to define what the driver behavior will be during a particular iteration. This includes whether the driver is glancing forward, what their reaction time will be, the type of maneuver selected to attempt to prevent the crash (which is always a braking maneuver in the simulation), and the effort used in that maneuver (e.g., peak deceleration achieved). Similarly to the lead vehicle, the following vehicle's deceleration profile has a linearly-shaped increase until peak deceleration is reached, but the peak deceleration level is maintained until the deceleration maneuver is complete. Component 3.1.3.2 generates the outcome for the simulation.

Each simulation iteration is set to begin as the lead vehicle begins a deceleration maneuver. The outcome of the simulation is calculated by advancing the scenario's initial kinematics to observe whether the pre-determined reaction times and deceleration levels for the following vehicle, given a pre-determined following distance, are sufficient to avoid a crash with a lead vehicle decelerating following a pre-determined braking profile. In the absence of an enhanced rear signal, or enhanced rear signal activation, none of these parameters are altered. However, if an enhanced signal is activated, first there is a check of whether the enhanced signal draws the eye (see earlier discussion of the *EyeDrawing* variable). If that is the case, then there are two potential reductions in the reaction time that may be applied:

- The pre-determined reaction time is reduced by a pre-calculated percentage, which is based on the empirical data available (see earlier discussion of the *ReactionReduction* variable)

- Pre-determined reaction times lasting longer than 2 sec are limited to last only 2 sec. In other words, reaction times are bound (on a percentage –based framework) for signals found to have an eye-drawing effect; this strategy is intended to limit the incidence of exceedingly long off-road glances.

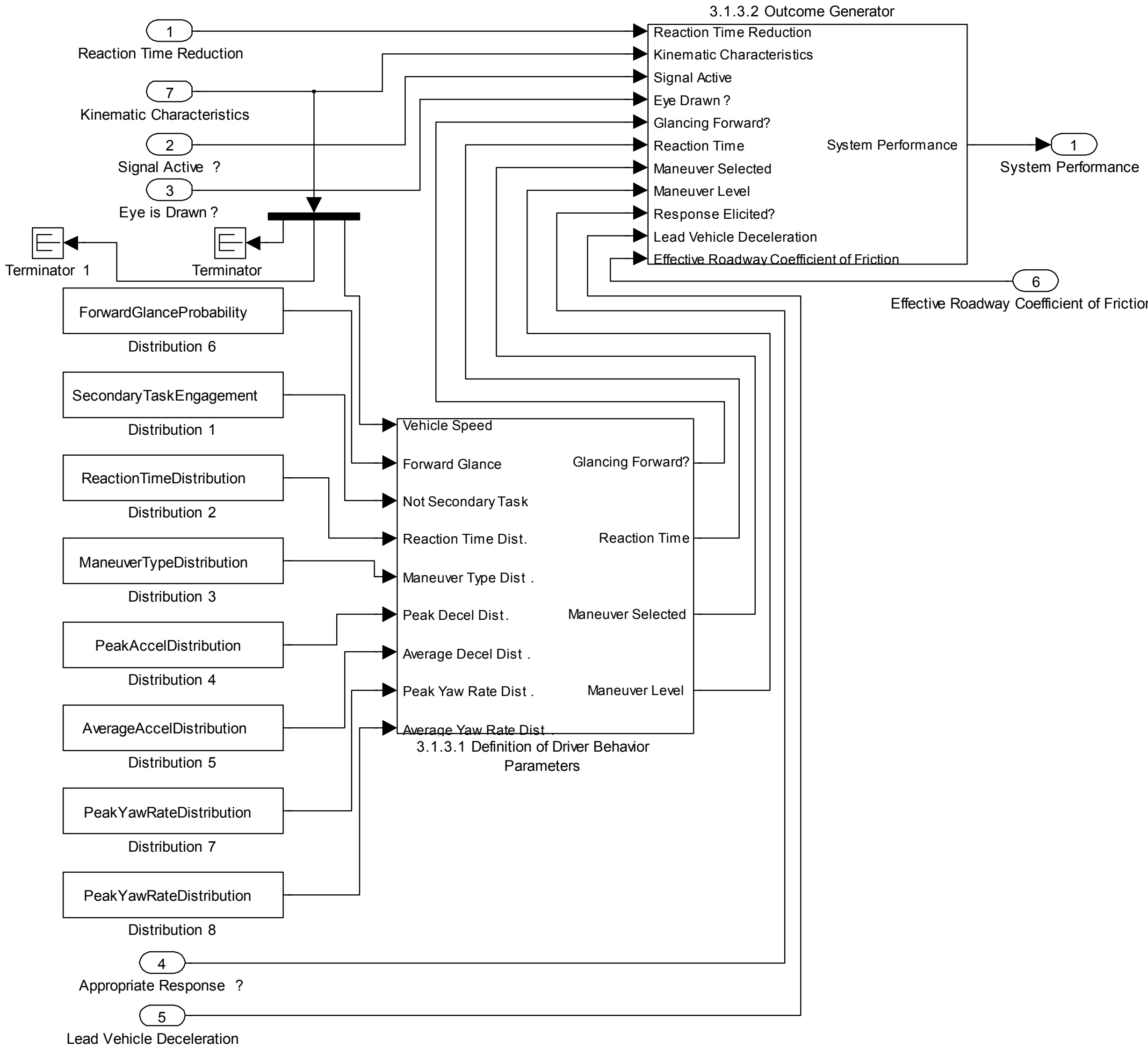

Figure 19. Module for the calculation of iteration outcome (3.1.3).

As the simulation progresses, time histories of a diversity of parameters are maintained. These parameters are:

- Outcome (whether a crash occurred or was avoided)
- Reaction Type (how the following vehicle driver reacted, e.g., by braking)
- Reaction Level (how much effort was expended in the response maneuver, e.g., peak deceleration)
- Reaction Time (how long it took for the following vehicle's driver to respond)
- TTC
- Following Vehicle Speed
- Lead Vehicle Speed
- Scenario State (i.e., the status of the signal activation, whether the following vehicle driver is reacting, how hard the lead vehicle is decelerating, and how hard the following vehicle is decelerating)
- Signal Activation Status

Once a simulation outcome is achieved (either a crash or avoidance), the output is provided to the control code for further processing, including the estimation of safety benefits.

Processing of simulation outputs and estimation of safety benefits

The control code uses the time-history output from the simulation to generate the following variables. Some of these variables (bold-faced) are used directly in the estimation of safety benefits. The remaining variables are stored to characterize the outcomes, as needed, with respect to the surrounding kinematic characteristics.

- **Crash – Takes a value of 1 if there was a crash, 0 otherwise**
- **Avoidance – Takes a value of 1 if a crash was avoided, 0 otherwise**
- **Final Relative Speed (in mph)**
- Initial TTC (in sec)
- **Was signal available to the following vehicle driver? (1 if yes, 0 otherwise)**
- **Was signal used by the following vehicle driver? (1 if yes, 0 otherwise)**
- **Type of following vehicle driver reaction (0 means braking)**
- Planned peak following vehicle deceleration
- Planned following vehicle jerk
- Actual peak following vehicle deceleration
- Actual peak lead vehicle deceleration
- Did the reaction time elapse before a crash occurred? (1 if it did, 0 otherwise)

- Reaction time – Either planned (if the previous value is 0) or actual (if the previous value is 1)

Once these outputs have been determined, the control code processes the next iteration until all the runs have been completed for cases with and without the availability of enhanced rear signals. The control code then processes these outputs to estimate potential safety benefits for the enhanced rear signal of interest under the pre-specified activation conditions.

The estimation of safety benefits is based on equations developed by Najm, Burgett, and others (W. Najm, Mironer, & Yap, 1997; Wassim G. Najm, 2003; Wassim G. Najm, daSilva, & Wiacek, 2000; Wassim G. Najm, Stearns, Howarth, Koopman, & Hitz, 2006; Wasim G. Najm, Wiacek, & Burgett, 1998; NHTSA Benefits Working Group, 1996), which have been used extensively for the past decade in the evaluation of numerous automotive collision avoidance technologies. The main outcome of the safety benefits estimation process is the predicted number of crashes potentially avoided annually following the deployment of a particular crash countermeasure, as follows:

$$C_A = C_{wo} \times D_C \times SE \quad \text{(Equation 1)}$$

Where:

C_A = annual number of the type of crashes of interest predicted to be avoided with a countermeasure's deployment

C_{wo} = annual number of the type of crashes of interest prior to a countermeasure's deployment

D_C = potential countermeasure deployment rate in the vehicle fleet

SE = System Effectiveness – proportion of relevant crashes expected to be prevented by the countermeasure of interest

Another potential safety benefit is related to crash mitigation, and re-expresses equation 1 in terms of the reduction in harm due to those crashes that occur.

$$H_R = H_{wo} \times D_C \times SR \quad \text{(Equation 2)}$$

Where:

H_R = predicted annual reduction in harm for the type of crashes of interest with a countermeasure's deployment

H_{wo} = annual total harm for the type of crashes of interest prior to a countermeasure's deployment

D_C = potential countermeasure deployment rate in the vehicle fleet

SR = System Harm-Reduction Effectiveness – estimated total effectiveness of the countermeasure in reducing the harm caused by the types of crashes of interest

There are three primary measures of interest that may have an impact on the estimation of the potential safety benefits for enhanced rear signals:

- System Effectiveness
- System Harm-Reduction Effectiveness
- Countermeasure Deployment Rate

The countermeasure deployment rate is beyond the scope of this effort and will be assumed to be 100%. System Effectiveness (*SE*) is calculated as follows:

$$SE = 1 - \frac{P_w(C)}{P_{wo}(C)} \qquad \text{(Equation 3)}$$

Where:

$P_w(C)$ = probability of the type of crashes of interest occurring with the countermeasure present

$P_{wo}(C)$ = probability of the type of crashes of interest occurring without the countermeasure present

The *SE* can also be re-expressed to consider two separate proportions as a function of the conflict(s) of interest, one dealing with the probability of exposure to a particular conflict, the other one representing the probability of a crash given that the driver is involved in a particular conflict. The first proportion is typically known as the exposure ratio, the second as a prevention ratio. These proportions are combined with the probability that a particular conflict is encountered prior to a crash. Written on an individual conflict basis:

$$SE_i = P_{wo}(S_i|C) \times \left(1 - \frac{P_w(S_i)}{P_{wo}(S_i)} \times \frac{P_w(C|S_i)}{P_{wo}(C|S_i)}\right) \qquad \text{(Equation 4)}$$

Where:

$P_{wo}(S_i|C)$ = probability that, given there is a crash, it resulted from conflict *i* if the countermeasure is not present

$P_w(S_i)$ = probability that conflict *i* occurs if the countermeasure is present

$P_{wo}(S_i)$ = probability that conflict *i* occurs if the countermeasure is not present

$P_w(C|S_i)$ = probability that conflict *i* results in a crash if the countermeasure is present

$P_{wo}(C|S_i)$ = probability that conflict *i* results in a crash if the countermeasure is not present

At a top level, the System Harm-Reduction Effectiveness (*SR*) is based on a comparison of the estimated relative harm associated with the crashes that occur while the countermeasure is present to the estimated relative harm when there is no countermeasure present.

$$SR = 1 - \frac{P_w(C) \times \bar{H}_w}{P_{wo}(C) \times \bar{H}_{wo}}$$ (Equation 5)

Where:

$\bar{H}_w$ = average harm for the type of crashes of interest occurring with the countermeasure present

$\bar{H}_{wo}$ = average harm for the type of crashes of interest occurring without the countermeasure present

As done for the SE, the SR can also be calculated on an individual conflict basis. The calculation uses the prevention and exposure ratios for each conflict to modify the average harm observed with and without the countermeasure for crashes preceded by a particular conflict type. Harm is calculated based on the number and/or type of fatalities within particular conflict categories and countermeasure states. This ratio is then weighted by the relative harm represented by different conflict types, which considers both the severity of injuries and their frequency. Equation 5 can be expressed as:

$$SR_i = H_{wo}(C|S_i) \times \left(1 - \frac{P_w(S_i)}{P_{wo}(S_i)} \times \frac{P_w(C|S_i)}{P_{wo}(C|S_i)} \times \frac{\bar{H}_w(C|S_i)}{\bar{H}_{wo}(C|S_i)}\right)$$ (Equation 6)

Where:

$H_{wo}(C|S_i)$ = relative harm for the type of crashes of interest occurring without the countermeasure present in conflict *i* Estimated to be 100,000 functional years life lost based on Najm, et al. (W.G. Najm, Smith, & Yanagisawa, 2006).

$\bar{H}_w(C|S_i)$ = average harm for the type of crashes of interest occurring with the countermeasure present in conflict *i*

$\bar{H}_{wo}(C|S_i)$ = average harm for the type of crashes of interest occurring without the countermeasure present in conflict *i*

The overall SE and SR values can then be obtained by summing equation 5 values and equation 6 values, respectively, across conflict types that collectively represent the complete crash problem. These estimates for SE and SR can then be input into equations 1 and 2 to obtain prediction of potential crashes avoided and crash mitigation (reduction in harm). Calculation of the different variables within each equation (see subsequent discussion) is completed within the SIM, using either pre-determined parameters or the output of the simulation process.

Calculation of the probabilities needed to estimate these benefits using the results of the SIM is straightforward and based on proportions of simulation cases with certain outcomes. To calculate system effectiveness, the probabilities are obtained as follows:

- $P_{wo}(S_i|C)$: assumed to be 1 since only one type of scenario was considered. The total number of annual crashes was assumed to be 428,000 based on the 37 crashes report (W.G. Najm, Smith et al., 2006)
- $P_w(C|S_i)$: obtained directly from the Monte Carlo simulation as follows:

$$P_w(C|S_i) = \frac{\textit{Number of crashes observed in a simulation run with the countermeasure present}}{\textit{Number of conflicts in a simulation run}} \quad \text{(Equation 7)}$$

- $P_{wo}(C|S_i)$: obtained directly from the Monte Carlo simulation as follows:

$$P_{wo}(C|S_i) = \frac{\textit{Number of crashes observed in a simulation run with the countermeasure absent}}{\textit{Number of conflicts in a simulation run}} \quad \text{(Equation 8)}$$

- $P_w(S_i)$: obtained directly from the Monte Carlo simulation as follows:

$$P_w(S_i) = \frac{\textit{Number of conflicts occurring in a simulation run with the countermeasure present}}{\textit{Number of iterations in a simulation run}} \quad \text{(Equation 9)}$$

- $P_{wo}(S_i) =$ obtained directly from the Monte Carlo simulation as follows:

$$P_{wo}(S_i) = \frac{\textit{Number of conflicts occurring in a simulation run with the countermeasure absent}}{\textit{Number of iterations in a simulation run}} \quad \text{(Equation 10)}$$

In turn, $\bar{H}_w(C|S_i)$ and $\bar{H}_{wo}(C|S_i)$ are estimated as follows:

$$\bar{H}_w(C|S_i) = \sum_i \sum_j P_w(I_j|C|S_i) \times w(I_j) \quad \text{(Equation 11)}$$

Where:

$P_w(I_j|C|S_i)$= probability of an injury of type *j* given a crash occurring in conflict *i* with the countermeasure present

$w(I_j)$ = coefficient of maximum fatality severity based on the impact speed differential, estimated from Figure 16 of Najm (2003)

$$\bar{H}_{wo}(C|S_i) = \sum_i \sum_j P_{wo}(I_j|C|S_i) \times w(I_j) \quad \text{(Equation 12)}$$

Where:

$P_{wo}(I_j|C|S_i)$= probability of an injury of type *j* given a crash occurring in conflict *i* with the countermeasure present

$w(I_j)$ = coefficient of maximum fatality severity based on the impact speed differential, estimated from Figure 16 of Najm (2003)

Chapter 5. Model Results

The computer-based SIM model described in the previous chapter was used to estimate safety benefits for several different potential enhanced signal approaches. Although the SIM had "placeholders" for all combinations of flashing pattern, luminance, and location, only some combinations were tested, corresponding to the combinations for which empirical data existed. In addition to these three characteristics, in some cases the simulation was run on particular activation criteria that modified the probability and timing of an enhanced signal activation. The specific combinations of flashing pattern, luminance, location, and activation characteristics tested were the following:

- Dual lighting levels @ 420 cd: For this condition, different daytime and nighttime brake lamp luminance levels were used. The brake lamps were illuminated in steady burn mode (i.e., no flashing). The daytime luminance level was 420 cd, whereas the nighttime luminance level was 130 cd. There was no signal timeout (i.e., the lights remained illuminated until the resolution of the simulation trial into either avoidance or a crash). Activation was not dependent on ABS activation, the violation of a minimum-TTC threshold, or a minimum speed.
- Dual lighting levels @ 840 cd: This option was the same as the previous enhanced signaling approach, except that the daytime luminance level was 840 cd (in contrast to 420 cd for the previous option).
- Recommended enhanced system proposed in Task 1 (Simultaneous 5Hz flashing @ 420 cd): This condition used the same enhanced signaling approach regardless of time of day. The brake lamps were flashed at 5 Hz with a luminance of 420 cd. Note that although the recommend Task 1 system had a luminance level of 1420 cd, the empirical tests indicated no difference between flashing 1420 cd signals and flashing 420 cd signals. Therefore, the less bright (and arguably, less potentially annoying) option was selected. The activation threshold was 0.35 g. There was no signal timeout. Activation was not dependent on ABS activation, the violation of a minimum-TTC threshold, or a minimum speed.
- Simultaneous 5Hz flashing @ 130 cd with activation threshold at 7 m/s^2 trigger (analogous to the "Mercedes-type" system approach): This condition used the same enhanced signaling approach regardless of time of day. The brake lamps were flashed at 5 Hz with a luminance of 130 cd. There was no signal timeout. The activation threshold was 7 m/s^2. Activation also occurred if ABS activated*. No activations occurred if the vehicle was traveling at less than 31 mph. Activation was not dependent on the violation of a minimum-TTC threshold.
- Simultaneous 5Hz flashing @ 130 cd: This condition used the same enhanced signaling approach regardless of time of day. The brake lamps were flashed at 5 Hz with a

luminance of 130 cd. The activation threshold was 0.35 g. There was no signal timeout. Activation was not dependent on ABS activation, the violation of a minimum-TTC threshold, or a minimum speed.

- Increased luminance (Steady burn at 420 cd with a 0.7 g activation threshold) analogous to a “Volvo-type” system approach: This condition used the same enhanced signaling approach regardless of time of day. The brake lamps were illuminated with a steady luminance of 420 cd. There was no signal timeout. The activation threshold was 0.7 g. Activation also occurred if ABS activated*. Activation was not dependent on the violation of a minimum-TTC threshold or a minimum speed.
- Closed Loop TTC-based Activation (Time-To-Collision values of 1.5, 2.0, and 2.5 sec): For these conditions, the recommended enhanced system proposed in Task 1 is used in a closed loop environment, where activation is dependent on a minimum TTC threshold being violated. Recall that for that system: 1) the same enhanced signaling luminance was used regardless of time of day; 2) the brake lamps were flashed at 5 Hz with a luminance of 420 cd; 3) there was no signal timeout; 4) for activation to be possible, a deceleration threshold of 0.35 g had to be exceeded (in addition to TTC requirements); and 5) activation was not dependent on ABS activation or a minimum speed,
- Timeout Effects (Different time-based signal timeouts @ 2, 5, and 10 sec): For these conditions, the recommended enhanced system proposed in Task 1 is used in conjunction with different signal timeouts. Recall that for that system: 1) the same enhanced signaling luminance was used regardless of time of day; 2) the brake lamps were flashed at 5 Hz with a luminance of 420 cd; 3) activation occurred if a deceleration threshold of 0.35 g was exceeded; and 4) activation was not dependent on ABS activation, the violation of a minimum-TTC threshold, or a minimum speed.
- Activation Threshold Effects (Different deceleration triggering criteria with activations @ 0.35g, 0.5g, and 0.7g): For these conditions, the recommended enhanced system proposed in Task 1 is used in conjunction with different signal activation thresholds. Recall that for that system: 1) the same enhanced signaling luminance was used regardless of time of day; 2) the brake lamps were flashed at 5 Hz with a luminance of 420 cd; 3) activation was not dependent on ABS activation, the violation of a minimum-TTC threshold, or a minimum speed.
- ABS Activation*: For this condition, the recommended enhanced system proposed in Task 1 is used in conjunction with ABS activation as a triggering criterion exclusively (enhanced signal activation only occurred if ABS was active). Recall that for that system: 1) the same enhanced signaling luminance was used regardless of time of day; 2) the brake lamps were flashed at 5 Hz with a luminance of 420 cd; 3) activation was not dependent on the violation of a minimum-TTC threshold, or a minimum speed.

** - Note that for the ABS Activation condition and for those conditions that used ABS activation as a triggering criteria, the method used in the model to determine ABS activation was simplistic. ABS was assumed to activate if adjustable maximum deceleration thresholds were exceeded. The thresholds varied* *according to wet or dry road conditions. Wet road conditions triggered ABS activation when deceleration exceeded 0.65 g, whereas dry road conditions triggered ABS activation when deceleration exceeded 0.90 g.*

Each of the above referenced rear signaling treatment conditions was simulated across a total of 12,500 crash conflict situations. These were distributed across 25 model runs with outputs for each experimental treatment compared to a common baseline comparison point. The results for each of these conditions are shown in Table 4. Note that the figures shown below are based on the empirical data collected, and that a number of assumptions were used in attempting to make these data conform to inputs that would be useful for the model. Therefore, caution should be used in interpreting these estimates. The descriptions of the conditions on the table are abbreviated, please refer to the list above for detailed descriptions of the different enhanced signaling treatments that were examined.

The results suggest estimated potential benefits for conditions involving enhanced signals that flash simultaneously at 420 cd, and to a lesser degree at130 cd, which is consistent with the results of the empirical tests. Post-hoc pair-wise comparisons between the different closed-loop TTC-based activation, timeout, and activation threshold conditions and the "baseline" (i.e., the "Flashing at 420 cd" condition) showed no statistically significant differences at the $\alpha=0.05$ significance level. In general, it appears that at a practical level, the model does not predict any detrimental effect because of imposition of a timeout to the enhanced signal. However, it is likely that this factor would have a large effect in cases where lead vehicles have been stopped for a substantial amount of time (e.g., > 2 sec). Those cases were not considered in the simulation. The closed-loop activation tended to nominally reduce observed effectiveness in the range of threshold values tested, although no significant differences were detected. Similarly, increases in the activation threshold, especially once the threshold is shifted upwards of 0.50 g, nominally reduced the benefits of the enhanced signal.

Table 4. Simulation results. Standard errors are shown in parentheses. Benefits significantly larger than zero are boldfaced. A value of "0" indicates the model output was not statistically different from zero.

Simulation Condition	System Effectiveness (SE)	Potential Crash Reduction in Annual Crashes	System Harm Reduction (SR)	Potential Harm Reduction*
Dual lighting levels @ 420 cd	ns	ns	ns	ns
Dual lighting levels @ 840 cd	ns	ns	ns	ns
Simultaneous Flashing at 420 cd (equivalent to 840 cd and 1420 cd based on empirical tests), with an activation threshold of 0.35 g.	**4.3% (1.0%)**	**18,592 (4,182)**	**8.6% (1.2%)**	**8,603 (1,179)**
Simultaneous Flashing at 130 cd, with an activation threshold of 7 m/s^2.	ns	ns	ns	ns
Simultaneous Flashing at 130 cd, with an activation threshold of 0.35 g.	**1.4% (0.7%)**	**6,003 (2,960)**	**3.3% (1.5%)**	**3,275 (1,471)**
Steady burn at 420 cd, with an activation threshold of 0.70 g.	ns	ns	ns	ns
<u>Closed Loop TTC-based Activation</u> Simultaneous Flashing @ 420 cd (equivalent to 840 cd and 1420 cd based on empirical tests) with activation at 0.35 g.				
- 1.5 sec TTC	ns	ns	**2.9% (1.3%)**	**2,935 (1,346)**
- 2.0 sec TTC	**1.9% (0.8%)**	**8,192 (3,379)**	**5.6% (1.4%)**	**5,584 (1,414)**
- 2.5 sec TTC	**2.4% (0.7%)**	**10,430 (3,177)**	**5.9% (1.2%)**	**5,880 (1,232)**
<u>Timeout Effects</u> Simultaneous Flashing @ 420 cd (equivalent to 840 cd and 1420 cd based on empirical tests), with activation at 0.35g				
- 2 sec Timeout	**5.1% (0.8%)**	**21,723 (3,269)**	**10.1% (1.2%)**	**10,132 (1,196)**
- 5 sec Timeout	**4.6% (0.8%)**	**19,774 (3,241)**	**8.9% (1.1%)**	**8,930 (1,141)**
- 10 sec Timeout	**4.1% (0.8%)**	**17,345 (3,267)**	**7.8% (1.1%)**	**7,833 (1,076)**
<u>Activation Threshold Effects</u> Simultaneous Flashing @ 420 cd (equivalent to 840 cd and 1420 cd based on empirical tests)				
- 0.35 g	Same as "Simultaneous Flashing at 420 cd"			
- 0.50 g	**3.7% (0.7%)**	**15,635 (2,937)**	**5.4% (1.2%)**	**5,408 (1,243)**
- 0.70 g	ns	ns	**4.6% (1.1%)**	**4,571 (1,142)**
ABS Activation	ns	ns	ns	ns

* - in functional years life lost

Discussion of Model Results & Limitations

Model results suggest that enhancements to the design of rear brake lighting signals may lead to improved performance relative to the standard conventional brake lighting, reducing the estimated number and severity of rear-end crashes. Of the brake signal configurations tested, those which simultaneously flash the brake lamps (both outboard and CHMSL units) at 5 Hz were found to be effective, reducing the crash rate by as much as a 5.1%, equivalent to 21,723 fewer annual rear-end crashes; these signals were also found to impact crash severity levels. None of the other brake signal approaches tested were found to significantly reduce the rear-end crash rate or crash severity level, this includes increasing signal luminance levels for steady-burn lamps (i.e., dual intensity lighting levels).

The model also found that effectiveness of the simultaneous flashing signal was moderated by both 1) signal luminance and 2) activation (or triggering) criteria. Flashing signal configurations with luminance levels at or above 420 cd were found to be over three times more effective compared to signals with luminance levels set to 130 cd; observed effectiveness rates reported in Table 4 were 4.3% versus 1.4%, respectively under an activation threshold of 0.35g. Lowering the signal activation threshold (defined here in terms of a deceleration trigger), tended to improve system effectiveness. Of the three deceleration triggers modeled, only the 0.35g and 0.5g levels were found to yield significant system effectiveness estimates, reducing the crash rate relative to the conventional lighting. As shown in Table 4, reducing the activation threshold from 0.7g to 0.35g acted to increase signal effectiveness under the 130cd simultaneous flashing configuration, leading to reduced crash rates and crash severity levels. This latter result is based, in large part, on the expected incidence rate or frequency of these braking events – high deceleration braking events (e.g., 0.7g) are expected to be much less common than moderate braking events (e.g., 0.5g and 0.35g). This is supported by an analysis of over 500,000 braking events drawn from the 100-Car database performed by Lee et.al (2007). These researchers found that the distribution of braking events is negatively skewed.

As illustrated in Figure 20, the incidence of braking events with peak decelerations above 0.7g is relatively rare, occurring, on average, approximately once every 3,000 miles (0.3 times per 1,000 miles). Conversely, braking events with peak decelerations at or below 0.3g's occur much more frequently, with a rate of approximately 104 events per 1,000 miles traveled. The practical implication of this for the model is reflected in terms of exposure – the frequency with which the system is expected to activate. Use of a high deceleration level trigger (e.g., 0.7g) reduces exposure while a lower deceleration trigger (e.g., 0.35) increases it. The trade-off, of course, is the relative incidence of False Alarms wherein the system activates unnecessarily, and the risk associated with missing a true event (i.e., Miss rate). Previous work performed under this program suggests that activations based on a deceleration threshold trigger of 0.4g would result in a false alarm rate of approximately 3% and a miss rate of approximately 25%; increasing the activation threshold to 0.55g reduces the false alarm rate to 1.2%, but increases the miss rate to approximately 66%. Clearly, tradeoffs exist between activation thresholds and the relative incidence of false alarms, and missed detections. The model does not currently take into account the impacts or costs associated with false or nuisance system activations which may erode driver trust and responsiveness to these signals, as well as increase driver annoyance.

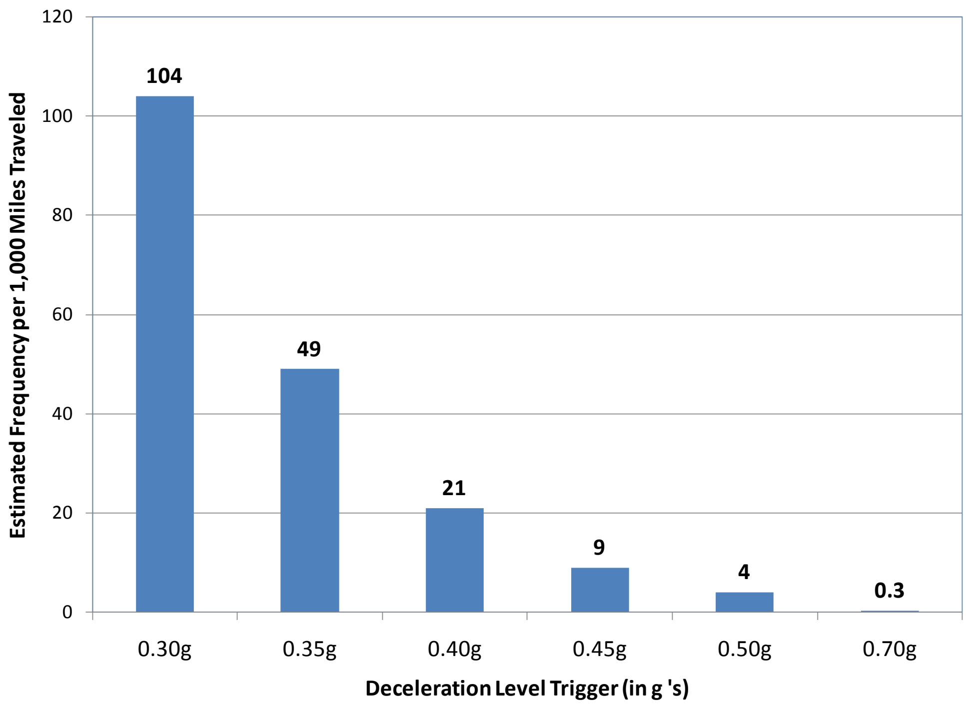

Figure 20 Estimated Rate of Occurrence Per 1,000 Miles Traveled (based on Lee et.al., 2007)

The following additional data is needed in order to refine and/or expand model outputs:

- Correlations between different model parameters, which are assumed to all be independent in the current model. For example, environmental conditions may have an effect on the probability of forward glances and the length of such glances; deteriorating conditions may exact more driver attention to the forward roadway.
- Unintended consequences and disbenefits associated with signal approaches. Many of these signals represent novel cues and may lead to unexpected driver behaviors, including undesirable and erratic responses to signals. Data is needed to quantify and characterize any unintended or undesirable behaviors signals are likely to induce. The model currently does not take into consideration potential system disbenefits.
- Driver acceptance and annoyance. Signals which are attention getting may also tend to be annoying. Wide scale implementation of signals perceived to be annoying may reduce overall system acceptance and desirability.
- Exposure rates quantifying the incidence with which a driver is not looking forward at the onset of a lead vehicle braking event. The effects of signals modeled here are essentially restricted to lead vehicle deceleration cases, and thought to act by drawing the driver's visual attention to the forward roadway or increase saliency of the lead vehicle. Data

which more precisely defines the rate of these situations (driver looking away at signal onset) will benefit model estimates.

- Performance data associated with other signal approaches including activation of the hazards.

Chapter 6. Work Plan for a Large-Scale Field Evaluation

Although useful and informative, data collected through controlled experiments is limited and may not provide an accurate assessment of the real world effectiveness of candidate rear-enhanced brake lights. In contrast, full-scale Field Operational Tests (FOT) which use instrumented vehicle fleets are better equipped to capture rear-conflict events consisting of crashes, near-crashes, and incidents, and subsequently provide a more solid foundation for estimating the effectiveness of various brake signal treatments. This FOT approach can more fully capture and represent a range of driving environments, situations, and conditions, and can serve to characterize and quantify important factors not easily captured through traditional methods such as potential unintended consequences. FOT's can also derive preliminary estimates of the reliability and effectiveness of signal approaches before wider implementation into the vehicle fleet. This section presents a work plan for the design and implementation of a large-scale Field Operation Test, intended to evaluate the relative safety benefits and effectiveness of different enhanced rear brake signaling approaches. The plan considers a number of factors and frames major issues and tasks required to support a large-scale evaluation study capable of assessing the relative benefits of enhanced rear lighting systems.

Study Sample Size and Duration

Both the sample size and duration of the FOT should be finalized, to a large degree, on the basis of the nature of the crash countermeasure itself and the number of expected system activations. Although the rear-end crash problem is characterized by a range of crash types (e.g., stopped lead vehicle, hard lead vehicle deceleration, etc.), this work plan is primarily tailored to the evaluation of systems designed to guard against rear –end crashes resulting from hard lead vehicle braking events. (Table 5 illustrates the expected number of system activations based on exposure (number of miles driven per month) and the deceleration levels used to trigger the onset of the rear signaling systems. The table also assumes the use of 100 vehicles with data collected over a 12-month period.

Two important points are illustrated by the table. First, use of a high mileage fleet (e.g., a taxicab fleet) is expected to yield significantly more frequent hard lead-vehicle braking episodes (system activations) than a comparable lower mileage population of drivers. While it is certainly possible to perform an FOT using a sample of drivers from the general driving public, it is likely that the sample size and or duration of the study would need to be much larger in scope than with a fleet evaluation. The difference becomes especially meaningful when performing analyses of eye drawing capability of the brake systems. Secondly, the specific criterion used to define hard braking and trigger the system also impacts heavily on the number of observed system activations.

Table 5. Initial Estimate of the Numbers of Events for Potential Study Conditions

	1,000 Miles/Month (General Population)				**4,000 Miles/Month (Taxi-Cab Driver)**			
Deceleration Criterion for Triggering System (g)	0.35	0.40	0.45	0.50	0.35	0.40	0.45	0.50
Activations Per 1,000 Miles	49	21	9	6	49	21	9	6
Expected Number Activations Per Vehicle	49	21	9	6	196	84	36	24
Number of Vehicles in Fleet/Study	100	100	100	100	100	100	100	100
Expected Number Activations Per Month for Fleet/Study	4,900	2,100	900	600	19,600	8,400	3,600	2,400
Months Data Collection	12	12	12	12	12	12	12	12
Total Number of Expected Activations	58,800	25,200	10,800	7,200	235,200	100,800	43,200	28,800

Estimates of the total number of crashes (or crash exposure rate) must also be considered. Exposure data based on an analysis of 100-Car Study data (Dingus et al., 2006) for rear-end events based on conflicts with a lead vehicle, suggest that rear-end crashes occur at a rate of 8.7 per million vehicle miles traveled (MVMT), near-crashes at a rate of 214 per MVMT, and incidents at a rate of 3,822 per MVMT. Based on these exposure rates, an FOT with 100 vehicles over the course of 12 months (with a total of 4,800,000 miles of travel based on an average of 4,000 miles per vehicle per month) would result in approximately 41 crashes, 1027 near-crashes, and 18,345 incidents. Nevertheless, rates of rear-end crash involvement specific to taxi cab fleets may not occur as often as general population vehicles. For example, Mortimer (1981) performed a 14-month FOT using 600 taxi cabs which resulted in 1,477 crashes of which only 325 were rear-end crashes; the study captured 41 million miles of travel. Only 197 (13%) of these involved the taxi cab being rear-ended – a crash exposure rate of 4.84 per MVMT. Recent DMV records for New York City cabs estimate a crash rate of 4.1 per MVMT for all crash types in 2004 (Schaller, 2006). Thus, the overall crash rate is still not expected to exceed the rate found through analysis of the 100-car dataset (8.7 per MVMT). Regardless of whether the FOT is conducted using a high-mileage taxi-cab fleet or drivers from the general driving population, crashes are rare events. Figure 21 illustrates the expected number of crash and near-crash events an FOT would be expected to generate given different sample sizes with data taken over a 12-month period using general population vehicles (to which the above reported crash rates). Clearly, analyses based on crashes alone would provide little substantive information regarding the effectiveness of the enhanced rear lighting systems unless an FOT is conducted with a very large number of vehicles. This continues to stress the need to develop and rely on surrogate crash measures and driver performance data in order to make efficient use of FOT resources.

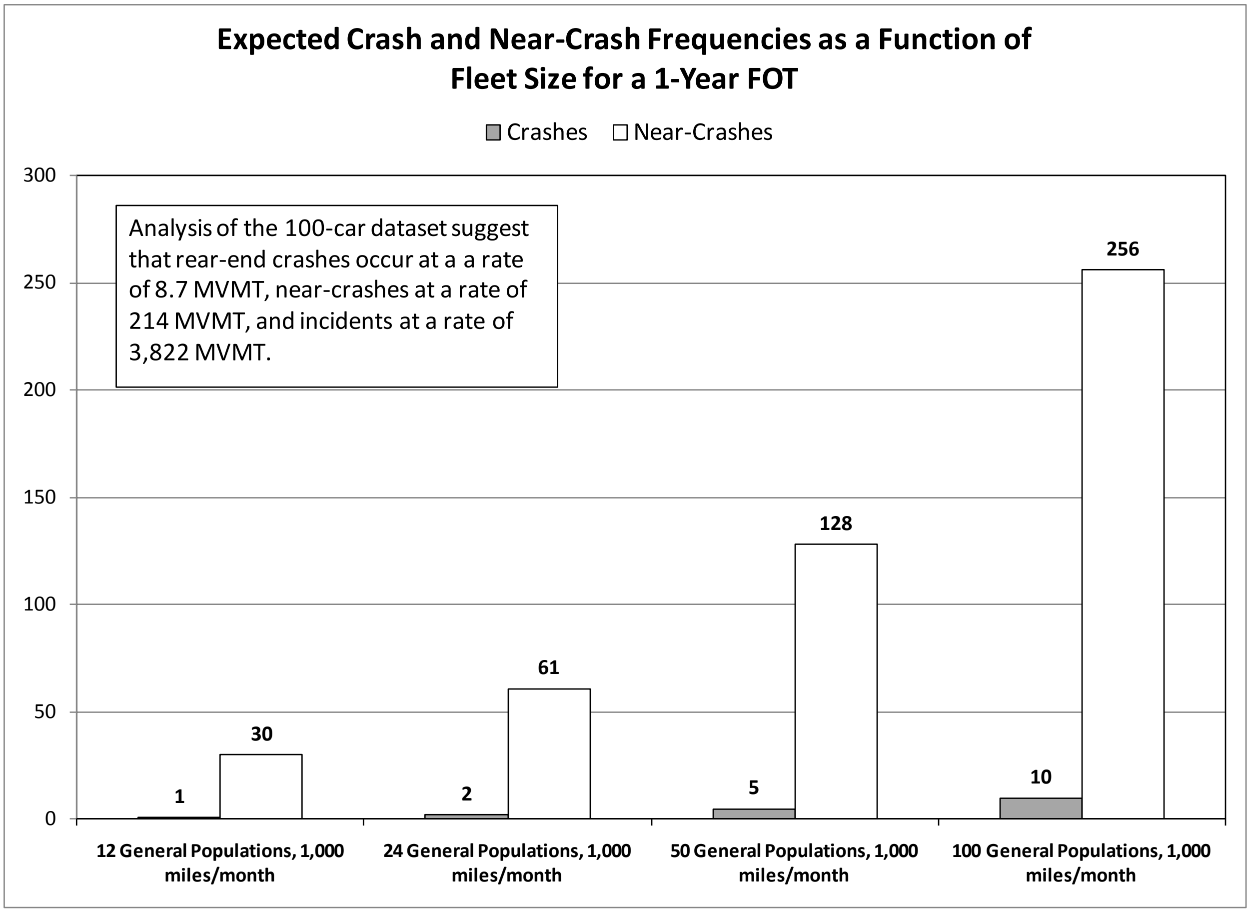

Figure 21. Comparison of Expected Event Frequencies by Study Design

Experience with the 100-Car Study and the limited data collection with the enhanced lighting systems in Task 2 of the current project suggests that urban environments are likely to evoke hard brake situations to a greater degree than freeway or rural driving environments; therefore the FOT should emphasize environments likely to yield system activations. Major metropolitan areas such as Washington DC and New York City also have taxicab fleets, providing the opportunity to conduct the study using vehicle fleets. If a taxicab fleet is enlisted, cabs operated by fleets or leased long-term (as opposed to owner-drivers) should be targeted, since they are in service more frequently during the course of a day (operating in shifts across multiple drivers) and average substantially higher mileage.

Fleet Type

This FOT serves as an opportunity to formally evaluate the performance benefits associated with particular lighting systems and configurations. Using a fleet of higher mileage drivers should increase the likelihood of reliably detecting differences across the experimental conditions (e.g., differences between conventional rear lighting and experimental lighting, as well as differences between experimental systems). As a result, NHTSA should consider recruiting taxi-cab drivers during the FOT as a means of increasing the sensitivity and power of the pilot effort.

An FOT using a fleet of vehicles (e.g., taxi cabs) offers some distinct advantages; fleets tend to have uniform vehicle types, with higher mileage (42,000 to 70,000 miles per year; Schaller Consulting, 2004). Although the actual crash and near-crash rates per MVMT are likely lower than the general driving population the higher rate of accumulated mileage should provide increased exposure. Taxicab fleets in particular should be considered as a viable candidate for an FOT having been used in past evaluations of enhanced rear signaling systems (Mortimer, 1981). The overwhelming majority of NYC taxicabs, for example, are Ford Crown Victorias, thus providing a uniform platform for installing these systems. The use of a single vehicle type would also minimize differences in the performance capability of the vehicles because it provides a consistent platform and viewing angle for the enhanced lighting system. Although the driving style of taxi-cab drivers may not be representative of most drivers, the focus is in the response of the following drivers because taxi cabs are likely to have more erratic driving and abrupt stops.

Using this type of approach would achieve the goal of exposing following drivers to the signal system under a wide range of scenarios, including high levels of braking as they are experienced in the normal course of driving.

Study Design of the FOT

It is expected that if desired, up to two candidate rear signaling systems could be evaluated during the FOT. Based on earlier findings reported in Task 1 (Wierwille et al., 2009) and Task 2 of this project, one of these candidate systems should be the Simultaneous Flashing of All Lamps at 5 Hz with a luminance of 420cd. This condition was comparable to the configurations which incorporated the same flash pattern but at an increased luminance (840cd and 1420cd), all of which outperformed the other candidate configurations tested. Other candidate designs could make use of the same simultaneous flashing approach with changes to luminance levels (e.g., 130 cd or 1420 cd), activation triggers (e.g., deceleration levels), or time-out algorithms (e.g., 5 sec, or 10 sec).

Experimental lighting systems could either be integrated into each study vehicle (each vehicle would be equipped with up to experimental lighting systems as well as conventional lighting), or across vehicles (a given vehicle would be equipped with a single experimental lighting system). In either case, periods of baseline data collection where the rear signaling systems are not active (the experimental lighting can be present but not active, or not physically present) should be included, allowing each experimental group to serve as their own control. Table 6 illustrates these alternative design approaches. Note that in either case, baselines are integrated into the data collection intervals. One advantage with this approach is that it requires fewer study vehicles to be instrumented. More importantly, it relies on a within-subjects design to minimize individual differences since drivers in each experimental lighting group will also provide data corresponding to the conventional brake light use.

Table 6. Alternative Designs

Study Groups	Experimental Lighting OFF (Baseline Data Collection)*	Experimental Lighting A ON*	Experimental Lighting B ON*
All Cars Equipped with Both Experimental Lighting Systems	4 months	4 months	4 months
*Counterbalanced orders across lighting conditions			

Study Groups	Experimental Lighting OFF (Baseline Data Collection)	Experimental Lighting ON
Vehicle Group A (Experimental Lighting A)	4 months	8 months
Vehicle Group B (Experimental Lighting B)	4 months	8 months

Within this basic framework, baseline data collection periods can be blocked across some fixed time interval (e.g., a continuous month) either before and/or after implementation of the supplemental lighting, or they may be woven within a series of smaller active versus inactive and novelty states to better account for uncontrolled factors such as traffic, weather, and time of year. Regardless of the specific design selected, the FOT will allow comparisons between experimental rear lighting configurations and conventional brake lighting. Since the experimental lighting systems are expected to be integrated into existing lighting housings (or be otherwise inconspicuous when inactive), use of a novelty condition to account for effects resulting from the introduction of a novel elements may not be required.

<u>Vehicle Instrumentation</u>

Each study vehicle should be equipped with an instrumentation system and experimental lighting system. The system should allow for acquisition and storage of high resolution video and potentially be mounted unobtrusively in the trunk area (i.e., 100-car-type data acquisition system). The same computer that collects the data should also control the lighting system. Data streams to be captured include acceleration (longitudinal and lateral), braking status, throttle status, speed, GPS, turn signal status, and rear facing radar data (to capture Following Vehicle speed, distance, TTC, headway, and acceleration). These data should be synchronized with the video data. NHTSA should also consider using a triggered data collection approach wherein data collection systems only record pre-specified events (high deceleration events). This will significantly reduce the amount of stored data and the frequency of data downloads. It is also recommended that the following components and or functions be included in the instrumentation suite:

- Up to three rear-facing cameras to capture the following vehicle driver's face; each with different focal lengths (approximately 200 ft, 100 ft and 50 ft). These cameras would provide information on eye-drawing capability of the signals, noting whether the following driver was glancing away from the roadway at the onset of the brake signal. Use of this set-up would enable surrogate safety eye-drawing measures to be used in addition to crash and near-crash measures.
- A single, center-mounted rear-facing radar unit. This may require that an offset license plate or a special plastic license plate be placed in front of the unit (which has the advantage of hiding the unit from public view). Another alternative would be to slightly offset the radar unit from the center (to the side of the license plate), and then carefully aim it to capture the following vehicle.
- An integrated lighting unit using existing rear lighting system (CHMSL or lower side mounted lamps). Depending upon the approach, study vehicles may have one or more experimental lighting systems installed. In either case, the conventional brake lighting systems should remain available and configured to operate as usual under ordinary braking conditions.
- A lighting controller to select and manage the operation of the experimental light system. The controller would be responsible for engaging the lighting and managing its durations and onset. It should also include a feature to automatically adjust the luminance level of the lights for nighttime use. The data acquisition system should also coordinate with this system in order to capture the state of the lighting.

<u>FOT Data Collection and Analysis</u>

The data collected during the FOT should be periodically downloaded, reduced, and analyzed as they become available. It is suggested that the following set of dependent measures, at minimum, should be analyzed (Table 7).

Table 7. Key Questions, Hypotheses, and Analyses

Measures of Observed Eye-Drawing of Following Driver		
Question	**Hypothesis**	**Cases, Metrics, and Analysis**
Are the experimental braking signals providing a benefit to following drivers who are looking away from the forward roadway at the onset of lead vehicle "braking"? To what extent do they capture and redirect the driver's gaze forward?	Previous work suggests that the experimental signals have an eye-drawing effect; a tendency to draw the driver's eyes forward compared to the conventional brake lights. It is believed this is due to the inherent properties of the experimental signals (flashing and brightness). This effect is expected to generalize to like situations in the real world.	Restrict cases to drivers who were observed to be looking away at the onset of the braking signal. **Latency for driver to look forward**, back to the roadway, following signal activation. Compare this value to baseline condition.

Measures of Observed Reaction of Following Driver		
Question	**Hypothesis**	**Cases, Metrics, and Analysis**
Are the experimental braking signals providing a benefit for following drivers who are looking forward at the onset of lead vehicle "braking"? (Eye-drawing component drops out, but do the signals provide additional benefit? To what extent do they evoke a braking response?)	Experimental signals are expected to serve as a salient and meaningful cue to drivers that the lead vehicle is "braking" (even under the tested conditions where the lead vehicle is not decelerating), and therefore drivers are expected to brake in response to the signals (at least initially). If this effect is demonstrated, it suggests that the signal is a powerful cue, evoking a brake response – independent of lead vehicle deceleration. Note: If the frequency of braking is comparable to baseline, this still is a positive piece of evidence – suggests that the experimental signals are not making the situation worse (drivers are responding by braking at the same rates as conventional signal) – drivers understand the meaning to be a braking signal.	Restrict cases to drivers who were observed to be looking forward at the onset of the braking signal OR simply use all cases, excluding those where we know the driver was looking off-road at the onset of the signal (landmark triggers). The assumption is that most drivers will likely be looking forward. **Incidence of subject vehicle braking events -** Compare percentages of braking events under experimental lighting to conventional braking signal. Examine brake activation rates over the entire 5 second exposure period, and up to 1 second after the signal extinguishes. **Brake reaction times** -Compare brake reaction times of the subject vehicle under experimental signals to conventional brake signal. Expect the experimental signals will yield faster brake response times, or at least equivalent response times to conventional signals (no delay in braking associated with experimental signals is also a positive result). **Brake duration -** Expected to be longer duration for experimental signals relative to conventional lights.

Are the experimental braking signals producing unintended or undesirable behavioral responses?	Signals are novel cues and may lead to unexpected behaviors. Signals are expected to be interpreted as a braking cue, and therefore should not produce negative behaviors (types of incidence of negative behaviors should be comparable to those exhibited under	**Erratic or evasive steering maneuvers** - Compare incidence of these events to baseline condition. **Braking for vehicles in adjacent lane (includes sudden, hard braking events)** - Compare incidence of these events to baseline condition. Only applies to multi-lane roadway, with an adjacent vehicle.

Event Measures of Interest	
Variable	**Description**
Minimum TTC	Minimum observed time-to-collision following onset of emergency brake light signal
Minimum Headway	Minimum observed headway following onset of emergency brake light signal
Maximum Speed reduction	Maximum observed speed reduction of following vehicle following onset of emergency brake light signal
Minimum Range	Minimum observed range following onset of emergency brake light signal
Event Classification	
Variable	**Description**
Crash	Any contact with an object, either moving or fixed, at any speed in which kinetic energy is measurably transferred or dissipated. Includes other vehicles, roadside barriers, objects on or off of the roadway, pedestrians, cyclists, or animals.
Near-Crash	Any circumstance that requires a rapid, evasive maneuver by the subject vehicle, or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. A rapid, evasive maneuver is defined as a steering, braking, accelerating, or any combination of control inputs that approaches the limits of the vehicle capabilities.
Incident	**Crash-Relevant Event -** Any circumstance that requires a crash avoidance response on the part of the subject vehicle, any other vehicle, pedestrian, cyclist, or animal that is less sever than a rapid evasive maneuver, but greater in severity than a "normal maneuver" to avoid a crash. A crash avoidance response can include braking, steering, accelerating, or any combination of control inputs. A "normal maneuver" for the subject vehicle is defined as a control input that falls outside of the 95 percent confidence limit for control input as measured for the same subject. **Proximity Event -** Any circumstance resulting in extraordinarily close proximity of the subject vehicle to any other vehicle, pedestrian, cyclist, animal, or fixed object where, due to apparent unawareness on the part of the driver(s), pedestrians, cyclists or animals, there is no avoidance maneuver or response. Extraordinarily close proximity is defined as a clear case where the absence of an avoidance maneuver or response is inappropriate for the driving circumstances (including speed, sight distance, etc.)

Suggested FOT Approach and Design

The following suggested approach and design, detailed in Table 8, is proposed in order to further specify and frame the implementation of a Field Operational Test intended to assess the effectiveness of an enhanced rear brake signal.

Table 8. Recommended FOT Study Approach and Design

Parameter	Recommendation	Rationale & Comments
Vehicle Fleet	Taxicab	▪ Increased exposure due to miles traveled. Also provides opportunity to capture a wider range of conditions and environments, including more daytime driving. ▪ Uniform vehicle platform affords more efficient vehicle instrumentation.
Sample Size & Duration	100 vehicles, 2 years	▪ A relatively large sample over an extended period of time is needed in order to generate a minimal number of crashes. Under normal conditions (with no treatment) it is estimated that 40 crashes would result using 100 taxis over the course of 2 years (assumes 4,000 miles per month, crash rate of 4.1 per MVMT.)
Rear Signal Treatment	Single experimental treatment using LED Lamps with Simultaneous Flashing @ 5Hz, and luminance of 420 cd. Signal trigger of 0.35g, and timeout after 5 sec	▪ Shown to be among the most effective signals based on empirical studies and model results. ▪ LED implementation should be possible with existing vehicle brake lamp housings. ▪ Although luminance levels would not require FMVSS exemption, use of flashing would require a special exemption.
Study Design	Longitudinal Within-Subjects, Repeated Measures with Treatment On/Off Periods	▪ Each vehicle is equipped with conventional and treatment signals, allowing each to serve as its own baseline with the experimental lighting phased on and off during the course of the 2-year study (e.g., 1 month on, 1 month off). Counterbalancing used for the fleet (half start with experimental lighting active). Controls for seasonal and other time-based effects.
Outcome Measures	Crashes, Near Crashes, and Eye-Drawing	▪ Some crashes would be anticipated to result over the 2 year period, but these would not be large numbers (estimate 20 under baseline conditions); this would provide some basis for comparison to the treatment condition. ▪ Up to 2,000 near crashes would be estimated to result over the course of the study period providing a much larger sample for analysis relative to crashes. Near crashes and incidents also provide a platform for analyzing signal eye-drawing effects.
Vehicle Instrumentation	Triggered Data Collection with DAS, including Rear Facing Radar (and Cameras, optional)	▪ Data Acquisition System to capture crash and near-crash episodes via radar and other on-board sensors. ▪ Use of triggered data collection minimizes data storage, and rear facing radar and optional cameras provides opportunity to assess effectiveness.

Chapter 7. Summary and Conclusions

This project, undertaken as part of a larger program of research sponsored by the National Highway Traffic Safety Administration and conducted by Virginia Tech's Transportation Institute, led to the development of a model designed to estimate the relative safety benefits of various enhanced braking signal approaches on the incidence of rear-end crashes, as well as the formulation of a detailed Work Plan for a large-scale rear signaling Field Operational Test (FOT).

The computer-based simulation model was implemented using Matlab's Simulink programming language, and serves as a useful decision-making tool allowing the identification and selection of promising rear brake signal approaches. It also provides a convenient framework for organizing and structuring available data, and was designed to be flexible and expandable allowing new information to be integrated as it becomes available. The model was exercised to assess the effectiveness of alternative signaling approaches using available data from published studies and reports, statistics on the crash problem from GES and associated database analyses, naturalistic studies or Field Operational Tests, as well as targeted rear lighting studies conducted under this research program.

Model results suggest that enhancements to the design of rear brake lighting signals may lead to improved performance relative to the standard conventional brake lighting, reducing the estimated number and severity of rear-end crashes. Of the brake signal configurations tested, those which simultaneously flash the brake lamps (both outboard and CHMSL units) at 5 Hz were found to be effective, reducing the crash rate by as much as a 5.1%, equivalent to 21,723 fewer annual rear-end crashes; these signals were also found to impact crash severity levels. The model also found that effectiveness of the simultaneous flashing signal was moderated by both 1) signal luminance and 2) activation (or triggering) criteria. The model does not currently take into account the impacts or costs associated with false or nuisance system activations which may erode driver trust and responsiveness to these signals, as well as increase driver annoyance.

Data from empirical studies conducted as part of this effort suggest that increasing the luminance of conventional steady-burn brake lamps does not appear to be an effective means of drawing attention to the brake signal; no performance gains were osberved at luminance levels of either 420 or 840 cd. In contrast, substantial performance gains may be realized by increasing brake lamp luminance levels under flashing configurations; detection rates under the 5Hz flashing lamp configurations increased to approximately 70% when luminance levels were increased to 420 cd – the current maximum luminance level allowable under FMVSS. However, increases beyond a certain luminance threshold will not return substantive performance gains, suggesting that the human eye does not respond in a linear fashion to changes in signal luminance. Signal viewing distance also appears to moderate detection performance.

Estimates generated by the model suggest brake signal effectiveness can be significantly increased by modifying the signal to include flashing at 5Hz under certain luminance and triggering conditions. The model also allows system design changes relating to triggering thresholds, signal duration, and luminance levels to be manipulated and modeled. Additional model results found the following:

- The most effective signal tested was found to have the following characteristics: simultaneous flashing @ 5Hz of both outboard and CHMSL units, luminance levels set to 420cd (currently the maximum allowable under FMVSS), a deceleration-based trigger threshold set to 0.35g, and a 2 second timeout following vehicle stop. This signal was found to reduce rear-end crashes by 5.1% and harm by 10.1%.
    - Reducing signal luminance to 130 cd under the simultaneous flashing configuration with activation at 0.35g lowered the estimated effectiveness of the signal (crash reduction of 1.4% and harm reduction of 3.3%)
    - Deceleration triggers set to a threshold of 0.7g were generally not effective in terms of yielding any significant crash reduction, but were found to have moderate harm reduction effects under the simultaneous flashing with 420cd.
- In general, the model does not predict any detrimental effect because of imposition of a timeout to the enhanced signal. However, it is likely that this factor would have a large effect in cases where lead vehicles have been stopped for a substantial amount of time (e.g., > 2 sec). Those cases were not considered in the simulation.

Estimates should be carefully interpreted since the model has not been validated, and is based on a set of underlying simplifying assumptions which restrict the scope based on the available data. Some model assumptions and limitations include the following:

- Restriction to rear-end conflicts characterized by lead vehicle deceleration events. The model is not intended to simulate rear-end crashes resulting from a stopped lead vehicle; however, it does include situations where the lead vehicle is stopped for less than 2 seconds, or the vehicle stops following a hard braking event.
- The model does not take into account changes in driver responses to the brake signals resulting from false system activations (model does not correct for system false alarm rates), nor does it consider any system-wide negative unintended consequences resulting from the enhanced brake signals (e.g., erratic responses, conflicts with turn signals, etc).

The following additional data is needed in order to refine and/or expand model outputs:

- Unintended consequences and disbenefits associated with signal approaches. Many of these signals represent novel cues and may lead to unexpected driver behaviors, including undesirable and erratic responses to signals. Data is needed to quantify and characterize any unintended or undesirable behaviors signals are likely to induce. The model currently does not take into consideration potential system disbenefits.

- Driver acceptance and annoyance. Signals which are attention getting may also tend to be annoying. Wide scale implementation of signals perceived to be annoying may reduce overall system acceptance and desirability.

- Exposure rates quantifying the incidence with which a driver is not looking forward at the onset of a lead vehicle braking event. The effects of signals modeled here are essentially restricted to lead vehicle deceleration cases, and thought to act by drawing the driver's visual attention to the forward roadway or increase saliency of the lead vehicle. Data which more precisely defines the rate of these situations (driver looking away at signal onset) will benefit model estimates.

- Performance data associated with other signal approaches including activation of the hazards.

A research work plan was also developed for implementing a large-scale Field Operational Test intended to evaluate the effectiveness of one or more rear signaling system implementations. This plan prescribes alternative means to empirically evaluate the estimated crash benefits of enhanced rear brake signal approaches via a Field Operational Test using a light vehicle fleet.

References

Federal Motor Vehicle Safety Standard 108: Lamps, reflective devices, and associated equipment, 49CFR571.108 (2004).

Lee, S. E., Llaneras, R.E., Klauer, S, Sudweeks, J. (2007) Analyses of Rear-End Crashes and Near-Crashes in the 100-Car Naturalistic Driving Study to Support Rear-Signaling Countermeasure Development Final Report Number DOT HS 810 846. Washington, D.C.: National Highway Traffic Safety Administration.

Najm, W., Mironer, M. S., & Yap, P. K. W. (1997). *DRAFT NHTSA Crash Avoidance System Benefits Estimation Report: Chapter 3 -- Preliminary safety benefits of a rear-end crash warning system* (Draft Report). Washington D.C.: Intelligent Transportation Society of America.

Najm, W. G. (2003). *Alternative methods for safety benefits estimation* (Project Memorandum No. HS316). Washington, D.C.: National Highway Traffic Safety Administration.

Najm, W. G., daSilva, M. P., & Wiacek, C. J. (2000). *Estimation of crash injury severity reduction for intelligent vehicle safety systems.* Paper presented at the Proceedings of the SAE 2000 World Congress, Paper No. 2000-01-1354, Detroit, MI.

Najm, W. G., Smith, J. D., & Yanagisawa, M. (2006). *Pre-Crash Scenario Typology for Crash Avoidance Research* (Report No. DOT-VNTSC-NHTSA-06-02): National Highway Traffic Safety Administration.

Najm, W. G., Stearns, M. D., Howarth, H., Koopman, J., & Hitz, J. (2006). *Evaluation of an automotive rear-end collision avoidance system* (Report No. DOT HS 810 569). Washington, D.C.: National Highway Traffic Safety Administration.

Najm, W. G., Wiacek, C. J., & Burgett, A. L. (1998). *Identification of precrash scenarios for estimating the safety benefits of rear-end collision avoidance systems.* Paper presented at the Proceedings of the Fifth World Congress of Intelligent Transportation Technologies, Seoul, Korea.

NHTSA Benefits Working Group. (1996). *Preliminary assessment of crash avoidance systems benefits* (Draft Report - Version II). Washington, D.C.: National Highway Traffic Safety Administration.

Mortimor, R. G. (1981). *Field Test Evaluation of Rear Lighting Deceleration Signals: II - Field Test* (No. DOT HS 806 125). Washington, D.C.: National Highway Traffic Safety Administration.

Schaller, B. (2006). *Taxicab and Livery Crashes in New York City 2004*. Brooklyn, NY: Schaller Consulting.

Schaller, B. (2004). *The New York City Taxicab Fact Book*. Brooklyn, NY: Schaller Consulting.

Wierwille, W. W., Llaneras, R.E., and Neurauter, M.L. (2009). *Evaluation of Enhanced Brake Lights Using Surrogate Safety Metrics: Task 1 Report: Further Characterization and Development of Rear Brake Light Signals* (No. DOT HS 811 127). Washington, D.C.: National Highway Traffic Safety Administration.

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